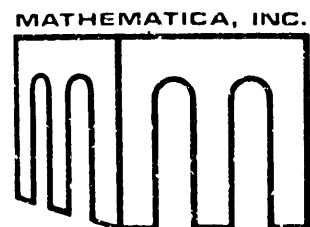


FINAL REPORT
DR MA-04

VOLUME I: EXECUTIVE SUMMARY

Prepared for
National Aeronautics & Space Administration
George C. Marshall Space Flight Center

Lockheed Missiles & Space Company, Inc.
Sunnyvale, California
and
Mathematica Inc.
Princeton, New Jersey



THIS SPACE INTENTIONALLY LEFT BLANK

**SPACE TUG
ECONOMIC ANALYSIS STUDY**

FINAL REPORT

DR MA--04

June 1972

VOLUME I: EXECUTIVE SUMMARY

Prepared For

National Aeronautics and Space Administration

Marshall Space Flight Center

Prepared By

Lockheed Missiles & Space Company, Inc.

Sunnyvale, California

and

Mathematica, Inc.

Princeton, New Jersey

**Lockheed Missiles & Space Company, Inc.
Sunnyvale, California**

FOREWORD

This report summarizes work accomplished under the Space Tug Economic Analysis Study on Contract NAS8-27709. This study was performed for the NASA Marshall Space Flight Center by Lockheed Missiles & Space Company, Inc. of Sunnyvale, California, and Mathematica, Inc. of Princeton, New Jersey. The period of technical performance was nine months, starting July 26, 1971.

The NASA Contracting Officer's Representatives for this program were Lieutenant Commander William C. Stilwell (USN) and Mr. Richard L. Klan. The study team was led by Mr. Charles V. Hopkins of Lockheed and Mr. Edward Greenblat of Mathematica. Task leaders on the Lockheed team were as follows:

John F. Skratt	--	Data Integration and Interpretation
William T. Eaton	-	Payload Data and Payload Effects Analysis
Richard T. Parmley	-	Tug Definition

Other key team members included:

Anthony G. Tuffo	-	Data Mechanization and Evaluation
Zoe A. Taulbee	-	Computer Programming
Jolanta B. Forsyth	-	Payload Costs and Benefits, Tug Cost Model
Kenneth J. Lush	-	Program Costing Logic

This report is divided into three volumes as follows:

- Volume I - Executive Summary
- Volume II - Tug Concepts Analysis
- Volume III - Cost Estimates

Volume I is a summary of the study approach, results, conclusions, and recommendations. It is arranged to conform to the outline contained in Data Requirement Description number DR MA-04 for contract NAS8-27709.

CONTENTS

	Page
FOREWORD	li
INTRODUCTION	1
Background	1
Study Objectives	2
Relationship to Other NASA Efforts	2
METHOD OF APPROACH AND PRINCIPAL ASSUMPTIONS	5
Technical Approach	5
Guidelines and Assumptions	11
BASIC DATA GENERATED AND PRINCIPAL RESULTS	13
Comparative Data Base Information	13
Comparison of Tug Concepts	16
Tug Sensitivity Analyses	29
Tug Funding and Phasing Considerations	39
Economic Analysis	41
Observations	56
Study Achievements	60
RECOMMENDATIONS	61
Study Limitations	61
Implications for Research	61
Suggested Additional Effort	62

ILLUSTRATIONS

Figure		Page
1	Overall Study Approach	6
2	LO ₂ /LH ₂ Tug Transportation Requirements vs Propellant Loading	18
3	LO ₂ /LH ₂ Tug Fleet Size vs Propellant Loading	18
4	LO ₂ /LH ₂ Tug Total Program Costs vs Propellant Loading	19
5	Reusable Space Tug Cost Comparison by Propellant Combination	20
6	Stage-and-one-half LO ₂ /LH ₂ Space Tug Costs	22
7	Expandable/Reusable Tug Cost Comparison	23
8	Ground Based/Space Based Tug Comparison	28
9	Cost Sensitivity to Shuttle User Fee	31
10	Cost Impact of Variations in Space Shuttle Capability	31
11	Cost Sensitivity to Payload Weight Growth	33
12	Total Program Cost Sensitivities to Tug Mass Fraction	34
13	LO ₂ /LH ₂ Space Tug I _{sp} Sensitivity	36
14	Cost Sensitivity to Tug Lifetime and Refurbishment Factor	38
15	Tug Funding Comparison	40
16	Comparison of Total Program Funding Requirements for a Delay of Six Years in Tug	42
17	Effect of Cost Uncertainty on Tug Economic Rankings	43
18	Economic Sensitivities to Major Variables	46
19	Typical Scenario Analysis Data Plots	49
20	Summary of Scenario Analysis Results	50
21	Distribution of Tug Benefits	54

TABLES

Table		Page
1	Tug Configurations Postulated for Study	4
2	Space Tug Design Characteristics and Costs	14
3	Space Tug Synchronous Equatorial Performance Characteristics	14
4	Space Tug Family Analysis	25

INTRODUCTION

Volume I is organized in accordance with the outline specified in the Data Requirement Description for this contract. The sequence of topics is as follows:

- Introduction
- Study Objectives
- Relationship to Other NASA Efforts
- Method of Approach and Principal Assumptions
- Basic Data Generated and Significant Results
- Study Limitations
- Implications for Research
- Suggested Additional Effort

For convenience, these topics are grouped under four chapters.

BACKGROUND

For the decade of the 1980s, the United States will replace its existing all-expendable launch systems with a new Space Transportation System (STS). The STS will comprise the Space Shuttle and a propulsive third stage generically designated as the Space Tug. For purposes of this study the term Space Tug designates any liquid propulsion stage under 100,000 lb propellant loading that is flown from the Shuttle cargo bay. Two classes of vehicles are included, namely:

- Orbit Injection Stages (existing stages, or derivatives thereof)
- Reusable Space Tugs

The design concepts selected for study under these two categories are listed in Table 1. These vehicle configurations, propellant combinations, and operating modes were deliberately chosen to provide a sampling that typifies the entire range of actual and potential Tug systems that could be operational by 1979.

STUDY OBJECTIVES

The expected results for this study, as reflected in the Statement of Work, were as follows:

- Total program cost comparisons for Tug concepts
- Total program cost sensitivities (to programmatic, configuration, and mode variables)
- Identification of driving economic parameters (design, operations, and payload factors) in the Tug system
- Recommendation of promising Tug concepts including sizes, configurations, and fleet inventories
- Analysis of early peak funding trends

As the study progressed, these objectives were broadened to include the generation of a full spectrum of quantified economic data bearing on Tug selection. This was done because (1) there is a wide range of criteria that NASA may apply in making the Tug selection; (2) all criteria do not yield the same choice; and (3) sensitivity factors may alter the selection process for any given criterion.

RELATIONSHIP TO OTHER NASA EFFORTS

The Space Tug Economic Analysis study complements Tug system definition work performed by NASA and other agencies, and it parallels the work performed for NASA under the Space Transportation System (STS) Economic Analysis study. Prior and concurrent studies involving Tug system definition are as follows:

<u>Performing Organization</u>	<u>Sponsor</u>	<u>Title</u>
Marshall Space Flight Center	NASA/MSFC	Conceptual Definition of Space Tugs for Earth Orbital Missions
McDonnell-Douglas (NAS7-101, SA 2465)	NASA/MSFC	Space Tug Point Design Study
North American Rockwell (NAS7-200, SA 2190)	NASA/MSFC	Space Tug Point Design Study

<u>Performing Organization</u>	<u>Sponsor</u>	<u>Title</u>
Lockheed Missiles & Space Co. Inc., (NAS9-11949)	NASA/MSC	Shuttle/Agena Compatibility Study
General Dynamics/Convair Aerospace (NAS3-14389)	NASA/LeRC	Compatibility Study of a Cryogenic Upper Stage with Space Shuttle
Boeing (NAS8-5608, subtask)	NASA/MSFC	Pre-Phase A Technical Study for Use of Saturn Derivatives to Determine an Optimum Space Tug
North American Rockwell (NAS9-10925)	NASA/MSC	Pre-Phase A Study for an Analysis of a Reusable Space Tug
McDonnell-Douglas (F04701-71-C-0173)	USAF/SAMSO	Orbit-to-Orbit Shuttle (Chemical) Feasibility Study
North American Rockwell (F04701-71-C-0171)	USAF/SAMSO	Orbit-to-Orbit Shuttle (Chemical) Feasibility Study
Messerschmitt-Boelkoy-Blohm	ELDO	Pre-Phase A European Space Tug System Study
Hawker-Siddeley Dynamics, Ltd.	ELDO	Pre-Phase A Study, European Space Tug

Tug design, operations and cost data from these studies were extracted, normalized to common guidelines and assumptions, and incorporated (as applicable) into the data base for the Space Tug Economic Analysis.

The S/S Economic Analysis study was performed jointly by Mathematica, Inc., Aero-Space Corporation, and Lockheed Missiles & Space Company. This study addressed the economics of the entire new Space Transportation System, (Space Shuttle, Reusable Space Tug) in comparison to all-expendable launch systems. Hence, although this study paralleled the Space Tug Economic Analysis in general subject matter, it was much less detailed in examining the Tug options than is the present study.

Table 1. TUG CONFIGURATIONS POSTULATED FOR STUDY

ORBIT INJECTION STAGES			REUSABLE SPACE TUGS	
	CURRENT STAGES	GROWTH VERSIONS	CURRENT STATE-OF-THE-ART DERIVATIVES	ADVANCED TECHNOLOGY
CONCEPTS	AGENA	LARGE TANK AGENA (LTA)	SINGLE-STAGE, LO ₂ /LH ₂ , RL10 ENGINE	SINGLE-STAGE, LO ₂ /LH ₂
	CENTAUR D-1T	GROWTH TANK (GT) CENTAUR		TANDEM-STAGE, LO ₂ /LH ₂ STAGE-AND-A-HALF, LO ₂ /LH ₂ SINGLE-STAGE, LF ₂ /LH ₂ SINGLE-STAGE, FLOX/CH ₄
BASELINE MODE	EXPENDABLE	EXPENDABLE	REUSABLE, GROUND-BASED, RETRIEVAL	REUSABLE, GROUND-BASED, RETRIEVAL
ALTERNATE MODES	NONE	NONE	1. EXPENDABLE 2. PLACEMENT ONLY	1. EXPENDABLE 2. PLACEMENT ONLY 3. SPACE BASED

METHOD OF APPROACH AND PRINCIPAL ASSUMPTIONS

TECHNICAL APPROACH

The overall approach used by Lockheed and Mathematica to perform the Space Tug Economic Analysis study is illustrated in Figure 1, a highly simplified diagram of study data flow. As this figure shows, there were three major steps in the analysis:

1. Building the data base (Lockheed task)
2. Integrating the data and interpreting the processed information (Lockheed task)
3. Performing the economic analysis (Mathematica task)

Data Base

The data base comprised: (1) design and cost data for the candidate Tug concepts, and (2) design and cost data for the unmanned spacecraft in the mission model. The nature and extent of information contained in the data base is summarized in the following paragraphs.

Tug Data Base. The principal sources of information used in building the Tug data base were prior and concurrent Tug studies (as listed in the previous chapter), and internal Lockheed analyses of space propulsion stage designs and costs. These elements of the data base were then normalized, i.e., adjusted for differences in constraints, guidelines and assumptions, so that all design and cost information conformed to a common baseline. Finally, the normalized data were used to synthesize reference concepts on which further data base work could be founded.

From the standpoint of design and cost data, the orbit injection stages were treated as point designs because existing OIS vehicles have established sizes and their growth

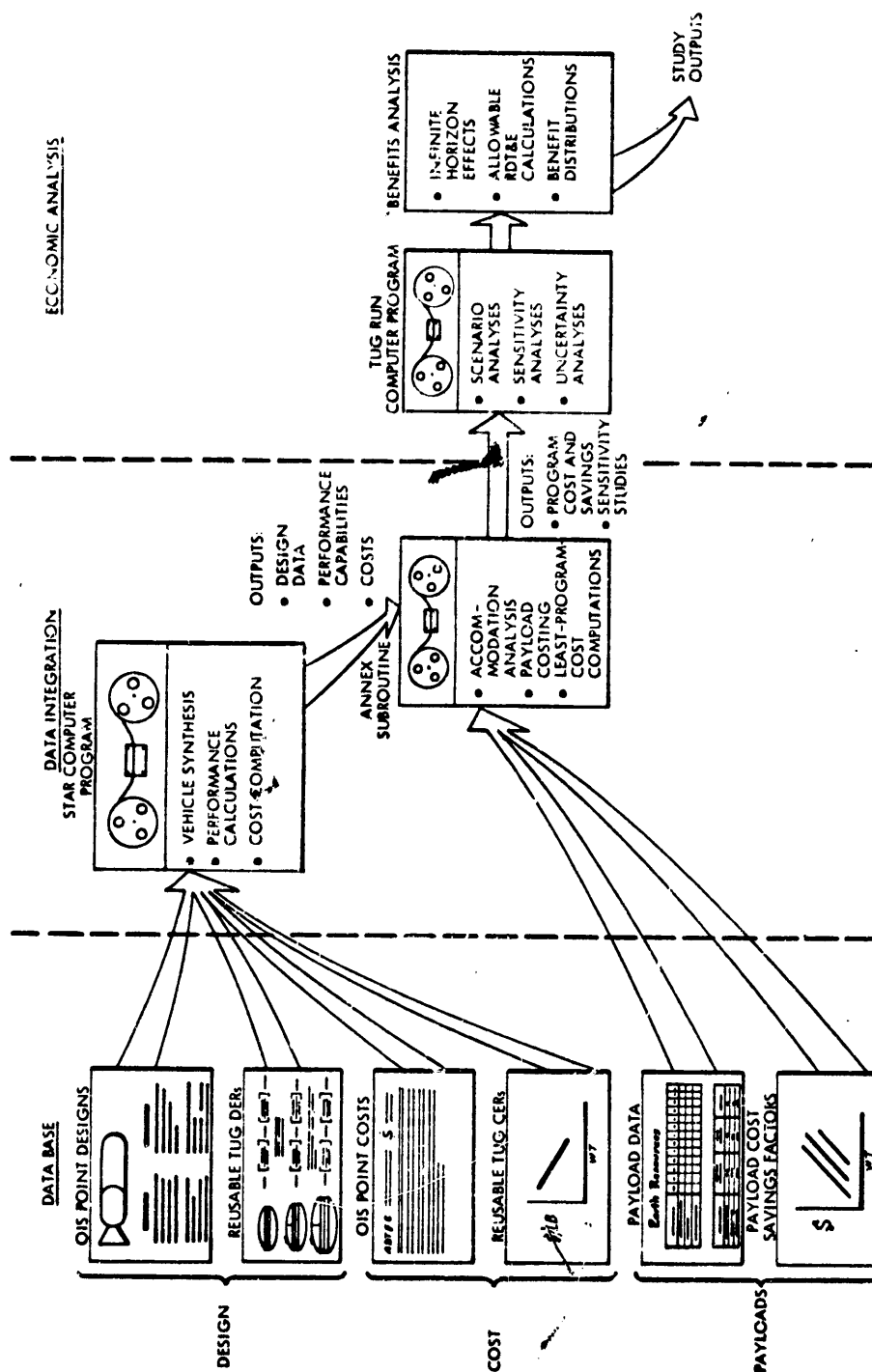


Figure 1. Overall Study Approach

versions are fairly well defined. The reusable Space Tugs were treated parametrically in the design and cost data bases so that sizing variations could be considered along with other configuration and operations variables.

To produce the parametric design and cost data needed for analysis of reusable Space Tug configurations, the following steps were taken:

- Design: A system of parametric design estimating relationships (DERs) was generated for the various Tug propellant combinations, vehicle configurations, and basing modes. The DERs established the weights and dimensions of candidate Tugs as a function of propellant loading and flight mode. Weights and sizes were calculated using a detailed methodology that evaluated stage hardware down to major-assembly and in some cases component level.
- Cost: A Space Tug cost model was derived for this study. This model uses parametric cost estimating relationships (CERs) based on historical data, together with algorithms that reflect relative complexity factors, learning effects, and activity-level relationships. It calculates Tug RDT&E, investment (fleet buy), and operations costs based on inputs characterizing the design and weights of the particular Tug concept.

Payload Data. The final element in the data base was information on the payloads delivered by the Space Tug system. A mission model comprising 64 programs (483 spacecraft placements) was supplied to Lockheed as a starting point for this analysis. This model was limited to those missions for which a Tug is potentially required; hence it excluded low-earth-orbit spacecraft directly deliverable by the Shuttle alone. User agencies represented in the model were NASA (both the Office of Space Sciences and the Office of Applications), the Department of Defense, and various non-NASA applications agencies.

The orbital parameters, sizes, weights (by subsystem), power requirements, and flight schedules were tabulated for the baseline payloads supplied in the mission model. The costs for these baseline payloads were then calculated using a parametric cost methodology applied to the spacecraft weights and characteristics; the resulting costs were checked against comparable estimates derived by Aerospace Corp. in the STS Economic Analysis study and found to be in agreement.

Having established the baseline payload costs, the final step in the data base task was to develop algorithms to express the payload savings possible with Space Tug systems. Based on the work performed by Lockheed under the original Payload Effects Analysis study (NASw-2156) three classes of payload cost savings were identified for the Tug, namely:

- Mass/Volume: These are the savings possible when payload weight and volume capacity (in excess of baseline requirements) are available, and low-cost fabrication techniques can be used because of the relaxed design tolerances.
- Payload Retrieval and Reuse: These are savings achieved when a spacecraft retrieved from orbit is refurbished, experiments are replaced as needed, and the spacecraft is returned to operational service (in lieu of purchasing a new unit).
- Accessibility: These savings, formerly called risk acceptance, arise from the fact that less testing (both RDT&E and acceptance) can be allowed for spacecraft that are accessible for repair in case of failure on orbit.

The savings attainable with each of these three effects were quantified in the form of cost and weight estimating relationships, and other algorithms.

Data Integration and Interpretation

The process by which Lockheed processed and interpreted information from the data base involved a close man/machine interaction. Simple, high-speed computer programs were used extensively so that the widest possible numbers of variables could be incorporated into the analysis while maintaining a short turnaround time for individual cases. Lockheed used as its primary computer program the Space Transportation Analysis Routine (STAR) and a subroutine designated ANNEX that calculates total program costs. STAR and ANNEX are not optimization programs, but rather computational tools designed to extend the efficiency of systems engineers. Individual runs of STAR/ANNEX were made for each Tug configuration or sensitivity variation being studied. At the conclusion of each sequence of runs the data evaluation team reviewed STAR/ANNEX printouts to determine cost-driving factors such as the numbers of shuttle flights, Tug flight-mode shifts, and Tug inventory requirements.

Specific functions performed in the STAR/ANNEX program were as follows:

- Reusable Tug Design Synthesis. Using the parametric design estimating relationships supplied from the data base, reusable Space Tug configurations (and expendable versions thereof) were synthesized for propellant loadings and flight modes of interest in the study. Detailed (65-entry) weight summaries were generated and Tug dimensions were calculated for the selected configurations. Mass fractions were computed for all Tug concepts.
- Performance and Mission-Accommodation Analysis. Using the stage mass fraction data from the Design Synthesis routine, the performance capabilities of candidate Tugs and orbit injection stages were calculated for all applicable Tug flight modes and staging techniques. The Tug performance data was then integrated with Shuttle performance data (supplied by NASA), and reference payload weights and sizes (from the payload data base). In this way there was formulated a mission-by-mission assessment as to which payloads could be flown in which modes with a given Tug. Any excess payload capability was also noted.
- Tug Cost Analysis. The next step in the STAR/ANNEX logic was calculation of the Tug costs. OIS costs were entered directly because these were point values. Reusable Tug costs were calculated using the Space Tug cost model that was mechanized in STAR; this cost model used as input the weights and characteristics generated in the Vehicle Synthesis routine. Activity-level-dependent costs were calculated on the basis of preliminary fleet sizes and activity levels projected in the Accommodation Analysis.
- Payload-Effects and Total-Program-Cost Analysis. At this point the potential payload cost savings were calculated and the relative total-program costs (Tug costs, Shuttle user fees, payload costs) were computed. The logic of this routine was as follows. For any given Tug concept, STAR/ANNEX progressed through the mission model one program at a time. Using data on Tug capabilities and payload requirements established in the Accommodation Analysis - along with the payload-cost savings algorithms developed in the data base - the payload and transportation costs were calculated (on a discounted basis) for every flight mode under every mission. A mode-by-mode comparison was made to arrive at the least-cost way of performing each program in the mission model, and the resulting cost for the total program was, by definition, the least-cost way to apply a given Tug to the reference mission model under the stipulated set of variables (e.g., Shuttle user fee, Tug lifetime, stage design).
- Total Cost and Funding Requirements Analysis. This final routine in STAR/ANNEX produced a refined total-program cost plus the annual funding requirements for the given Tug and the given variables. The first step in this analysis was to recompute Tug activity-level-dependent costs based on the least cost mode mix derived in the previous step. These Tug operations costs were added to the Tug RDT&E and investment costs, the Shuttle user costs, and the payload costs to arrive at a total-program cost figure. This sum was time phased, using RDT&E and procurement spans along with standard statistical spread functions, to arrive at funding requirements by fiscal year.

Economic Analysis

Mathematica received direct outputs from the STAR/ANNEX program in punched-card format, and also hard copy printouts of the STAR/ANNEX runs. From this data base, Mathematica proceeded to process and interpret the Tug systems data from a purely economic point of view.

The Mathematica approach to data analysis, as did the Lockheed approach, featured a close man/machine interaction. Mathematica used a computer program called TUGRUN, adapted from an earlier version called SCENARIO, to mechanize the performance of economic sensitivity analyses. Using TUGRUN, the following sensitivity analyses were performed:

Programmatic Variables

- Mission Scenario
- Shuttle User Fee
- Payload Refurbishment Factor
- Payload Cost Uncertainty

Tug System Variables

- Tug RDT&E Cost Uncertainty
- Tug Operations Cost

The outputs of TUGRUN were evaluated and interpreted manually. Additional runs were made to expand or clarify the analysis.

Other elements of the Mathematica economic analysis were performed manually. These included the calculation of allowable RDT&E costs and the analysis of Tug program benefits. Allowable RDT&E costs were computed in the following way:

1. Tug recurring cost benefits (i.e., savings in payload and transportation costs referenced to the best orbit injection stage) were calculated at a 10 percent discount rate.
2. These benefits were extended indefinitely in time by the so-called "infinite horizon" technique.

3. The discounted benefits were summed and converted back to undiscounted costs spread across the time period in which RDT&E expenditures would be made. This gave the allowable RDT&E expenditures, referenced to the baseline OIS vehicle; by subtracting the estimated RDT&E costs for a particular Tug concept from the allowable values, an economic margin was derived to express the net advantage or disadvantage of that concept.

Mathematica also analyzed the distribution of benefits by user agency, energy level, and source, as well as by time-phasing.

To approach the problem of Tug time phasing and fleet-mix composition, Mathematica developed (through feasibility demonstration) a computer program called OPCHOICE. This program used mixed-integer programming techniques.

GUIDELINES AND ASSUMPTIONS

The following guidelines were stipulated by NASA for this study:

- Constant-Year Dollars. Constant-year dollars were used throughout the study. By mutual agreement the selected year was 1970, so as to be compatible with the STS economic analysis.
- Shuttle User Fee. This was set at \$5 million per flight regardless of the numbers of Shuttle flights required. However, the effects of across-the-board increases in this fee were explored parametrically.
- Mission Model. The Shuttle/Tug system was considered to be introduced at a 1979 initial operational capability (IOC) date at full capability. No phased buildup of the new Space Transportation System was assumed. Parametric variations in the total number and composition of the missions in the model were explored.
- Reusable Space Tugs. The baseline propellant combination was LO_2/LH_2 and the baseline engine specific impulse was 460 seconds. Variations in both were explored.
- Orbit Injection Stages. Cryogenic OIS vehicles had a baseline specific impulse of 444 seconds and earth-storable OIS concepts, a maximum of 310 seconds.
- Discount Rate. A 10 percent social rate of discount was used throughout the study.
- Prime Contractor Fee. This fee was excluded from all study costs; however, subcontractor/supplier fees were included.

Additional assumptions made by Lockheed/Mathematica were as follows:

- Missions Requiring Expendable Tug. For missions in which a stage must be expended (e.g., planetary probes) it was assumed that a reusable Tug approaching the end of its design lifetime (not necessarily the end of its useful lifetime) would be flown. For these missions, only the recurring-operations charge was assessed.
- Tug Fleet Production Rate. For reusable Tug fleets of relatively small size it was assumed that production would occur at an efficient rate (i.e., 5 per year or more) so that the costs of sustaining a manufacturing base would be minimized.

BASIC DATA GENERATED AND PRINCIPAL RESULTS

The results and findings of the Space Tug Economic Analysis are discussed in this chapter. Specific topics covered are as follows:

- Comparative data base information
- Comparison of Tug concepts
- Tug sensitivity analyses
- Tug funding analysis
- Economic evaluation of Tugs
- Observations
- Study achievements

These are discussed at length in the ensuing sections.

COMPARATIVE DATA BASE INFORMATION

To compare and contrast the principal Space Tug and OIS concepts studied under this contract, summarized performance, design, and cost data for these concepts are presented in Tables 2 and 3. The design and cost data are summarized in Table 2. This information reflects the following trends:

- The configurations using earth-storable propellants (Agena and Large Tank Agena) and space-storables (FLOX/CH₄) are appreciably shorter and lighter than cryogenic Tugs of equal propellant loading.
- The RDT&E costs of orbit injection stages (including modifications for Shuttle compatibility) are low compared to the reusable Tugs.
- The RDT&E costs of reusable Space Tugs, calculated on a parametric basis, reflect relatively small differences between propellant combinations. This is because the weights of the fluorine-based systems are lighter than the LO₂/LH₂ configurations and the weight differences offset the complexity factors assigned the fluorine-propellant Tugs. However, the fluorine Tugs reflect an added cost uncertainty.

Table 2. SPACE TUG DESIGN CHARACTERISTICS AND COSTS

	SPACE TUG DESIGNATION	IMPULSE PROPELLANT WEIGHT (LB)	SPECIFIC IMPULSE (SEC)	VACUUM THRUST (LB)	INERT WEIGHT (LB)	STAGE LENGTH (FT)	RDT&E COST (\$M)	RECURRING PRODUCTION COST* (\$M)
ORBIT INJECTION STAGES	AGENA	13,400	290.8	16,100	1257	20.6	43.9	2.20
	LARGE TANK	51,100	310	17,100	1853**	23.8	51.5	2.59
	AGENA	30,000	444	30,000	4488	32.2	61.5	4.75
	D-1T CENTAUR	45,000	444	30,000	4252**	37.0	65.5	5.25
REUSABLE SPACE TUGS	LO ₂ /LH ₂	30,000	460	20,000	5100	28.7	501.7	15.84
	LO ₂ /LH ₂	36,300	460	20,000	5450	30.9	509.9	16.01
	LO ₂ /LH ₂	43,000	460	20,000	5850	33.1	518.9	16.20
	LO ₂ /LH ₂	50,200	460	20,000	6290	35.4	528.2	16.39
	LO ₂ /LH ₂	57,700	460	20,000	6760	37.9	538.0	16.59
	LO ₂ /LH ₂	50,200	444	15,000	6120	36.1	456.3	16.38
	LO ₂ /LH ₂	50,200	470	20,000	6290	35.4	548.2	16.39
	FLOX/CH ₄	44,000	414	20,000	4520	23.8	448.7	14.41
	FLOX/CH ₄	52,000	414	20,000	4980	25.1	469.7	14.58
	FLOX/CH ₄	58,900	414	20,000	5260	25.8	475.2	14.68
	LF ₂ /LH ₂	47,800	474.4	20,000	5440	28.1	576.2	16.57
	LF ₂ /LH ₂	54,200	474.4	20,000	5720	29.4	582.8	16.71
	LF ₂ /LH ₂	60,600	474.4	20,000	6010	30.6	589.4	16.86

*AVERAGE UNIT COST FOR OIS; THEORETICAL FIRST UNIT COST FOR REUSABLE TUGS. ALL VALUES EXCLUDE MISSION-PECULIAR SERVICES

**DRY INERT WEIGHT; ALL OTHER VALUES ARE WET INERT WEIGHT

Table 3. SPACE TUG SYNCHRONOUS EQUATORIAL PERFORMANCE CHARACTERISTICS

SPACE TUG DESIGNATION	IMPULSE PROPELLANT WEIGHT (LB)	PAYLOAD DELIVERY AND RETRIEVAL CAPABILITY* (LB)			
		MODE 1	MODE 2	MODE 3	MODE 4
AGENA	13,400	-	-	-	2,550
LARGE TANK	51,100	-	-	-	14,397/13,777
AGENA	30,000	-	-	-	13,318
D-1T CENTAUR	45,000	-	-	-	21,208/18,710
LO ₂ /LH ₂	30,000	-	280	790	14,418
LO ₂ /LH ₂	36,300	1016	1403	3,680	17,500
LO ₂ /LH ₂	43,000	1400	1997	5,777	21,320/19,740
LO ₂ /LH ₂	50,200	2475	3418	8,966/8,840	25,250/18,850
LO ₂ /LH ₂	57,700	3237/2827	4471	11,725/7,384	29,472/18,290
LO ₂ /LH ₂ (I _{SP} = 444)	50,200	1640	2320	6,840/5,850	23,600/18,530
LO ₂ /LH ₂ (I _{SP} = 470)	50,200	2645	3680	9,480/9,140	26,640/19,820
FLOX/CH ₄	44,000	1380	1870	5944	19,430/18,837
FLOX/CH ₄	52,000	2147	2883	8,411/8,310	22,700/17,640
FLOX/CH ₄	58,900	2910/2690	3911	11,410/7,825	26,180/17,475
LF ₂ /LH ₂	47,800	3390	4720	12,020/11,890	25,980/20,310
LF ₂ /LH ₂	54,200	4350	6060	15,430/11,314	29,970/20,085
LF ₂ /LH ₂	60,600	5340/4270	7435/7200	18,940/10,840	33,960/19,900

*UNCONSTRAINED TUG IGNITION WT/TUG CONSTRAINED TO 65K LB IGNITION WT

- Unit production costs for the orbital injection stages are low compared to the reusable Tugs; however, the unit cost of the reusable vehicles, when used in an expendable mode, drops by as much as one-half when the reuse hardware is deleted.

The comparative performance data are presented in Table 3; this performance data is for synchronous equatorial orbit. Four flight modes are referenced in this table, as follows:

- Mode 1. Roundtrip delivery of equal weight payloads by one Tug
- Mode 2. Retrieval, only, of a payload in one Tug roundtrip flight
- Mode 3. Delivery, only, of a payload in one Tug roundtrip flight
- Mode 4. Delivery of an expendable payload with no Tug return

In the Tug/payload round trip mode (Mode 1) the LF_2/LH_2 Tugs attain the maximum capability, followed by the LO_2/LH_2 and $FLOX/CH_4$ concepts. The expendable orbit injection stages have no capability in the reusable Tug modes (Modes 1, 2, and 3). Note that in Mode 4 (all-expendable) most of the Tugs can deliver a payload weight exceeding that of the largest synchronous equatorial spacecraft in the mission model.

Performance figures shown with two values divided by a slash mark represent cases in which the combined weight of the Tug and the payload exceed the Shuttle weight carrying capability. The figure on the left is the theoretical Tug capability unconstrained by the weight limitation, and the figure on the right is the Tug capability when constrained to the 65,000 lb due-east Shuttle payload capacity.

COMPARISON OF TUG CONCEPTS

The first output of the data integration and interpretation task was comparative data on the total program costs for candidate Tug concepts. Issues considered in this analysis were stage sizes, propellant combinations, vehicle configurations, expendable concepts, Tug families, and ground/space basing.

Baseline Reusable Tugs

Important variables in the relative ranking of Tug total program costs were payload savings captured, numbers of Shuttle flights, numbers of Tug flights required, and Tug fleet size. The variation in certain of these factors as Tug size is increased is illustrated in the baseline reusable Space Tug propellant combination (LO_2/LH_2). The total transportation requirements for ground based LO_2/LH_2 Tugs as a function of propellant loading are presented in Figure 2; the Tug fleet-size requirements are presented in Figure 3, also as a function of propellant loading. Both sets of data reflect two options in Tug staging, namely tandem capability in Modes 2 (dedicated retrieval) and 4 (all-expendable) only, and tandem capability in all modes. This is presented to assess the impact of increased tandem capability on the composition and level of transportation system requirements.

The transportation requirements presented in Figure 2 comprise the numbers of Tug flights and Shuttle flights needed to perform the total mission model for the two cases of tandem mode operation. The Tug flight requirements as shown for both these cases are broken into two values, the bottom line showing numbers of reusable flights and the upper line showing total numbers of Tug flights; these curves are additive so that the difference between the lines is the number of Tug flights in the expendable mode. The upper curve plots the required number of Shuttle flights. This figure includes multiple Shuttle flights for Tug/payload combinations too big to fit in the cargo bay. The selection of a given Tug system to fly in a reusable or expendable, single or tandem mode is predicated upon minimizing discounted program costs, and therefore is significantly influenced by the payload savings obtainable for a given mission. This is demonstrated by the fact that there is significantly increased flight activity for the

smaller Tugs when tandem stages are considered for all flight modes rather than for a limited number of modes only. While the number of Tug and Shuttle flights is greater in the case where tandem stages are possible in all four modes, the number of expendable Space Tug flights is significantly reduced, thereby reducing the Tug fleet size. Note that the numbers of Space Shuttle flights in excess of the total numbers of Space Tug flights remain relatively constant for the smaller Tug propellant loadings, but that in both cases as the Tugs become larger this delta number of flights increases because of greater numbers of Tug/payload length incompatibilities.

The Tug fleet size requirements (Figure 3) were derived by assuming the baseline lifetime values, namely a 30-use Tug design lifetime with the Tug being flown on an expendable mission at its 30th use. These curves show the total numbers of Tugs required (top line) and the numbers of reusable Tugs in the fleet (bottom line). The difference, then, is the number of Tugs required exclusively for expendable flights; such Tugs can be built without reuse and retrieval hardware. Where tandem stages are only considered in flight Modes 2 and 4 and the Shuttle and Tug flight activity is lower, the number of expendable Tugs that must be purchased drops sharply as the LO_2/LH_2 systems become increasingly capable of supporting single stage reusable missions. This fleet size approaches a constant of 17 reusable and 14 expendable Tugs. Where tandem stages are considered in all modes, the result of minimizing total program discounted costs produces a fleet size of approximately 20 reusable and no expendable Tugs, regardless of the propellant loading. The capability to tandem in all modes is economical, especially for the smaller Tug sizes, because the increase in the number of Shuttle and Tug flights is more than offset by the payload savings captured.

When all elements comprising the total program cost are quantified — including the transportation requirements, just discussed, and the payloads — then plots of undiscounted total program cost versus propellant loading can be derived. Typical curves for ground-based LO_2/LH_2 Tugs are presented in Figure 4. These graphs, based on a Shuttle user fee of \$5 million per flight, consider the same options in tandem mode

LO₂/LH₂ GROUND BASED

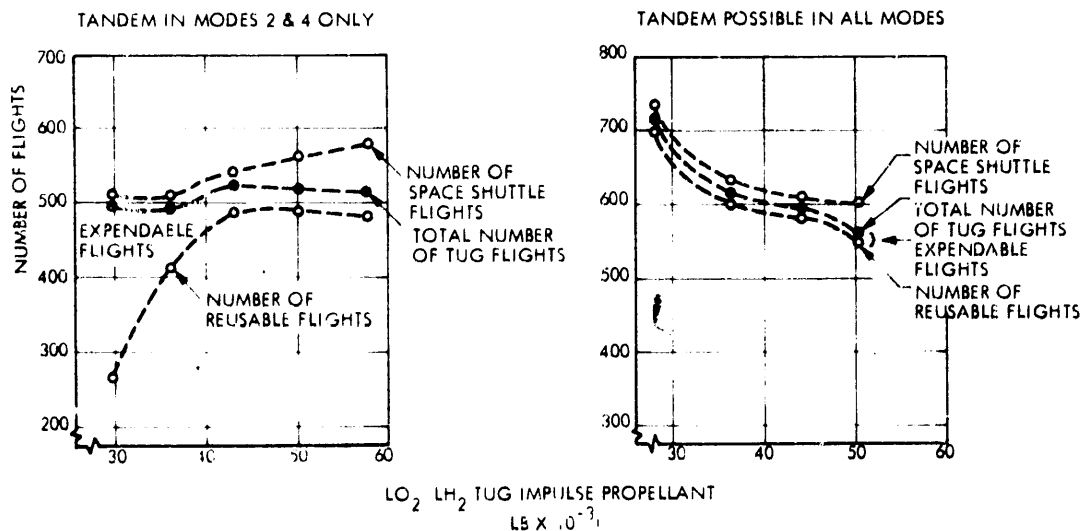


Figure 2. LO₂/LH₂ Tug Transportation Requirements vs Propellant Loading

LO₂/LH₂ GROUND BASED

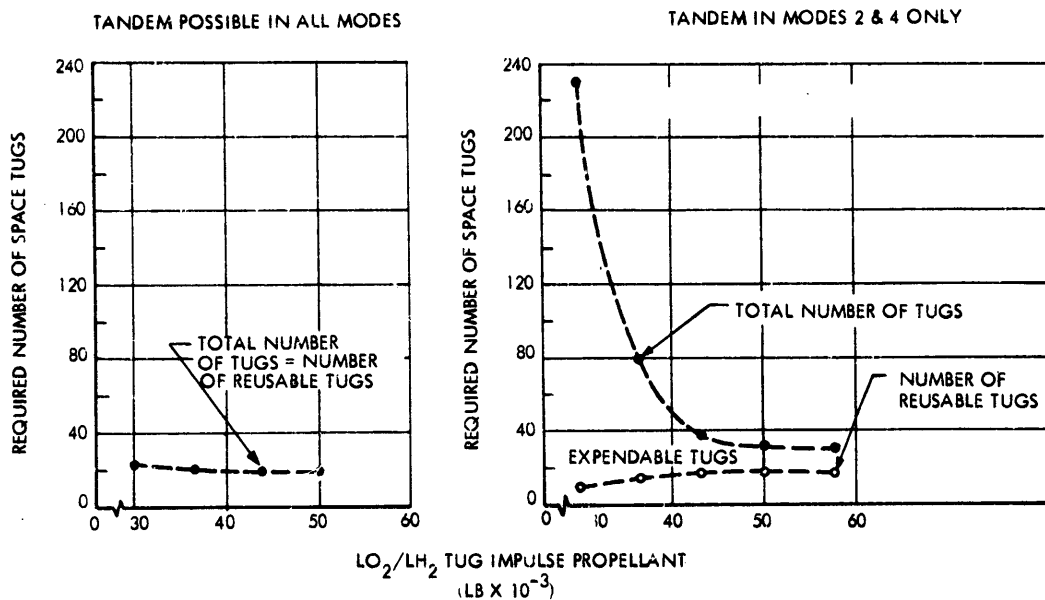


Figure 3. LO₂/LH₂ Tug Fleet Size vs Propellant Loading

operation as were considered under the transportation requirements analysis. The data points on these curves, which are additive, show that total program costs decline as propellant loading increases to about 50,000 lb, then increase slightly approaching 60,000 lb. The decline for both operating modes is caused by (1) increased capture of payload effects, and (2) declining Tug costs because of greater vehicle reusability. The slight cost increase approaching $W_p = 60,000$ lb arises from the increased Shuttle flight costs for Tug/payload combinations too long for a single Shuttle flight. With respect to the magnitude of these costs, note that (1) Payload costs predominate (approximately 80 percent of total), with Shuttle costs next (approximately 12 percent), and Tug costs the least magnitude at 8 percent of the total costs; (2) the absolute difference in costs between propellant loadings is appreciable (about \$1.4 billion maximum):

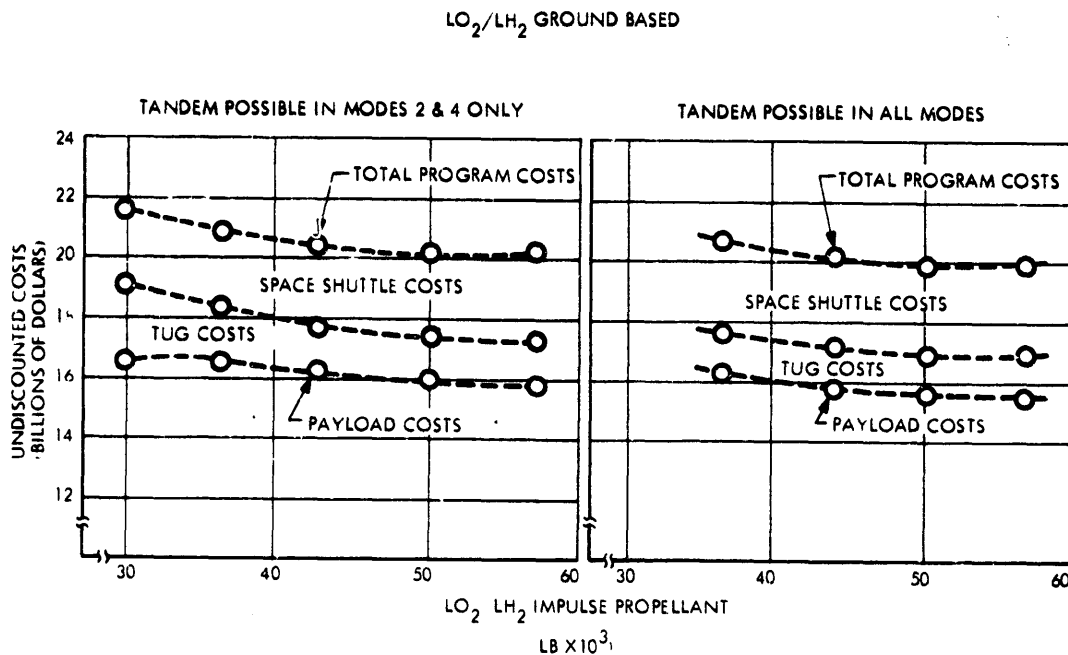


Figure 4. LO_2/LH_2 Tug Total Program Costs vs Propellant Loading

and (3) operational sequences in which tandem stages are considered for all flight modes cost approximately \$300 million less over the total mission model than the case which limits possible tandem stages to Modes 2 and 4 only. Note that on the graphs, the circles representing discrete data points can be interpreted as the profile of a smooth continuous function, as is represented by the dashed lines. In reality, however, the actual data between the discrete points represents discontinuous step functions that result from switches in payload effects captured, flight modes, and Tug and Shuttle activity requirements.

Reusable Tugs with Alternative Propellant Combinations

Having established the total program cost trends for reusable ground-based LO_2/LH_2 Tugs it is appropriate, next, to consider the other candidate propellant combinations. In Figure 5, the undiscounted total-program costs for Tugs using LF_2/LH_2 and FLOX/CH_4 propellants are plotted on a common scale with the LO_2/LH_2 costs just presented (all values are for tandem capability in Modes 2 and 4, only).

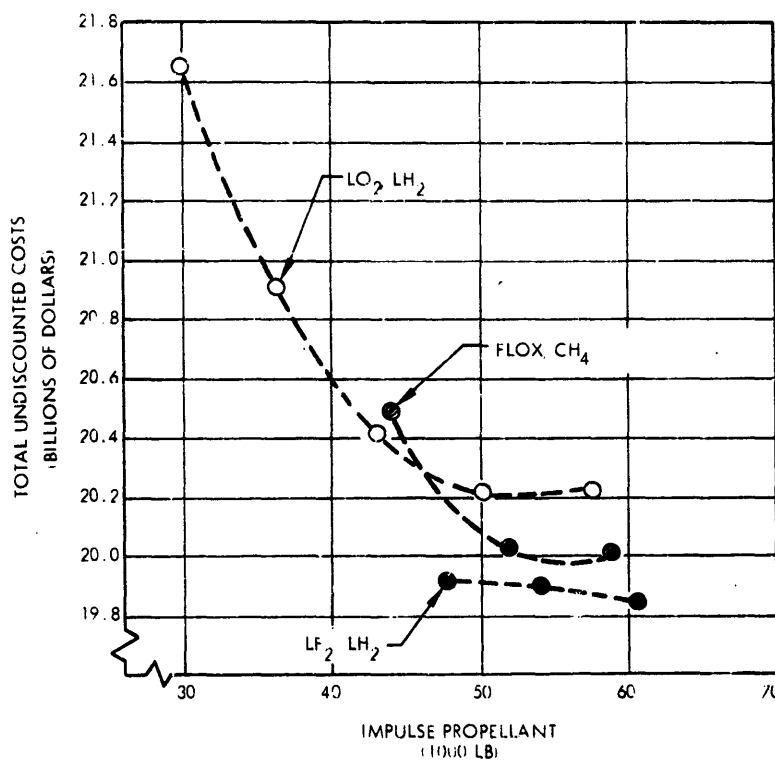


Figure 5. Reusable Space Tug Cost Comparison by Propellant Combination

These curves were built up from the same type of transportation and fleet-inventory requirements analyses as were the LO_2/LH_2 values. The following observations may be made from these results:

- Both LO_2/LH_2 and FLOX/CH_4 Tugs exhibit a tendency to reach apparent optimum propellant loadings, whereas the LF_2/LH_2 Tugs appear to be relatively insensitive over the range examined
- The LF_2/LH_2 and FLOX/CH_4 Tugs are both lower in total program costs (depending upon stage size) than the best LO_2/LH_2 stage by about \$200 to \$300 million undiscounted.
- Although the undiscounted-cost comparison slightly favors LF_2/LH_2 Tugs over FLOX/CH_4 configurations, the cost differences disappear when expenditures are discounted at 10 percent. This is because the FLOX/CH_4 costs are lower in the early time period (i.e., RDT&E, fleet buy) and are higher in the time period when discounting effects are greatest.

Stage-and-One-Half Tugs

Having compared various propellant combinations in single-stage Tug configurations, the next concept to be considered was the stage-and-one-half configurations in which expendable tankage was used with a reusable core stage. The undiscounted total program costs for stage-and-one-half LO_2/LH_2 Tug configurations are compared against single stage LO_2/LH_2 Tug costs in Figure 6. Important ground rules assumed for the stage-and-one-half concepts were as follows:

- The stage-and-one-half system was based on a reusable LO_2/LH_2 core stage with a 30,000 lb propellant loading; the core stage was 15 feet in diameter and represented the approximate lower limit of LO_2/LH_2 stage designs that still support the entire mission model.
- The drop tank set was defined as a single LH_2 tank with multiple clustered LO_2 tanks. The tank set was also 15 feet in diameter and was assumed to be mated to the core stage for purposes of launch in the Space Shuttle.
- The orbital flight sequence was defined so the tank set would be jettisoned at the target along with the payload, rather than when the tanks are depleted. This assumption means a decrease in performance capability compared with jettisoning the tanks at depletion but was made to circumvent the operational problems of ending a burn sequence prior to completing a total maneuver.

The three data points shown in Figure 6 represent the total stage-and-one-half propellant load (i.e., a 30,000 lb W_p core stage in combination with 18,000 lb, 24,000 lb and 27,000 lb W_p drop tank capacities). The 18,000, 24,000 and 27,000 lb loadings

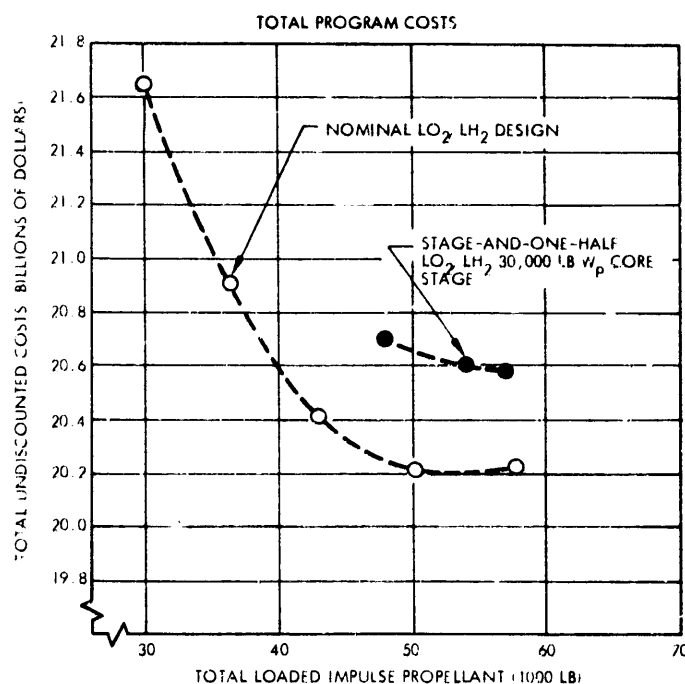


Figure 6. Stage-and-one-half LO_2/LH_2 Space Tug Costs

represent the largest capacities for 2, 3, and 4 clustered LO_2 tanks within the design estimating relationships used for the drop tanks. As was expected, the addition of the drop tank precluded the selection of tandem core stages for any of the missions in the model. The total cost figures shown do represent, however, a mix of using the core stage alone or in combination with the tank set based upon the minimum cost to support an individual program. Note that a 30,000 lb propellant stage, when used with a 27,000 lb drop tank set, saves over \$1.0 billion compared to using a single or tandem 30,000 lb stage without drop tanks. While the minimum differential with respect to a single large LO_2/LH_2 reusable Space Tug is approximately \$400 million over the 12-year mission model, variations in operational modes and core and tank set sizes could potentially reduce this figure.

Expendable Orbit Injection Stages

The comparison of Tug concepts then proceeded from the partially expendable stage-and-one-half concepts to the fully expendable orbit injection stages. Figure 7 compares the undiscounted total program costs of four OIS concepts (three stages and a best mix family of Agena and Centaur) against the costs for typical reusable Tugs (LO_2/LH_2 ,

tandem capability in Modes 2 and 4 only). The orbit injection stages, applicable to Mode 4 only, were evaluated on the basis of either single or tandem stages for every mission. For the expendable systems shown, nearly 100 percent of the low-cost payload savings associated with the expendable spacecraft were captured by all the vehicles. Transportation costs, therefore, account for the major difference between the expendable orbit injection stages themselves. The transportation costs are reflected in the numbers of Space Shuttle flights required (primarily a function of the OIS length), and in the user fee of the candidate systems. Although, on an undiscounted dollar basis the best expendables (the Agena/Centaur mix and the Large Tank Agena) are from \$300 million to \$600 million more expensive than the 30,000 lb W_p LO_2/LH_2 reusable system, on the basis of a 10 percent discount rate these same systems save from \$20 million to \$350 million with respect to the same 30,000 lb LO_2/LH_2 system. On this basis, the improper selection of a reusable Tug size can result in a system less economical than an all-expendable orbit injection stage system. As defined for the purposes of this study the most cost-effective OIS is the Large Tank Agena which is approximately \$1.7 billion undiscounted, or \$220 million discounted, more expensive than the best reusable LO_2/LH_2 system.

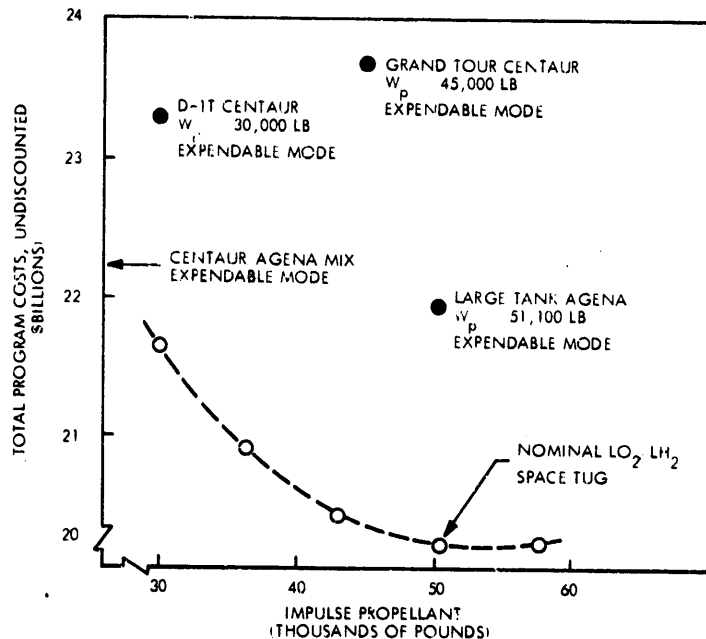


Figure 7. Expandable/Reusable Tug Cost Comparison

A separate comparison of orbit injection stages and reusable Tugs was performed to determine whether the transportation cost savings alone could justify development of the reusable Tug. A special analysis was conducted in which all payload retrieval modes were suppressed for a typical LO_2/LH_2 reusable Tug (48,500 lb propellant loading). The total program costs for this reusable Tug were compared against those for an optimum orbit injection stage (the Large Tank Agena). In this comparison the only payload savings were from mass and volume relaxation effects; payload-reuse and payload-accessibility savings were omitted. The results of this analysis show that the transportation cost savings are slender at best. On an undiscounted cost basis the reusable LO_2/LH_2 Tug shows a net advantage of approximately \$210 million, whereas on a discounted cost basis the LTA shows an advantage of around \$150 million. The difference is attributable to the fact that orbit injection stages incur maximum costs in the years when discounting effects are least pronounced (i.e., 1980-1990).

Tug Families

After considering various ground based Tug concepts individually, Lockheed explored the feasibility of grouping Tugs into families, with each family capable of performing the entire mission model. Three categories of Tug families were considered: (1) a small and a large reusable LO_2/LH_2 system with shared development costs, (2) a small LO_2/LH_2 reusable design plus an expendable tank set, and (3) a small LO_2/LH_2 reusable vehicle plus an orbit injection stage. It was assumed that these families would be developed so both vehicles would be available at the beginning of the mission model. Table 4 shows the family description(s) and the computed program costs, in undiscounted dollars. A common small LO_2/LH_2 reusable stage size, for all three categories, was defined as having a 20,000 lb propellant capacity in order to provide maximum differential in performance and size, thereby generating the greatest interaction with the other family member(s). These other members as shown were the 50,200 lb LO_2/LH_2 reusable Tug, a drop tank with the same 20,000 lb propellant capacity as the core stage, and the LTA orbit injection stage. Note that the figures for the 20,000 lb W_p LO_2/LH_2 reusable design reflect the fact that this system cannot perform, even in a tandem stage mode, one of the high weight, interplanetary missions but that in every case where a mix is defined the total mission model can be performed. The

Table 4. SPACE TUG FAMILY ANALYSIS

CANDIDATE TUG	NUMBER OF TUGS*	COSTS (\$ MILLIONS, UNDISCOUNTED)						TOTAL PROGRAM
		RDT&E	INVESTMENT		OPERATIONS		PAYLOADS	
			NON-RECURRING	RECURRING	ACTIVITY DEP.	ACTIVITY INDEP.		
LO ₂ /LH ₂ ** W _P = 20,000 LB	54	487.	434.	204.	4147.	82.	16,277	21,631.
LO ₂ /LH ₂ W _P = 50,158 LB	19	528.	386.	0	3419.	82.	15,563.	19,978.
MIX	6/12	647.	363.	0	3350.	82.	15,592.	20,034.
LO ₂ /LH ₂ ** W _P = 20,000 LB	54	487.	434.	204.	4147.	82.	16,277.	21,631.
MIX: STG + 1/2 LO ₂ /LH ₂ (CORE W _P = 20,000 LB + DROP TANK W _P = 20,000 LB)	26/302	533.	304.	104.	3321.	82.	16,131.	20,475.
LO ₂ /LH ₂ ** W _P = 20,000 LB	54	487.	434.	204.	4147.	82.	16,277.	21,631.
LTA W _P = 50,900	485	52.	0	1255.	2826.	0	17,814.	21,947.
MIX	14/219	539.	281.	566.	3144.	82.	16,479.	21,091.

*REUSABLE TUGS/EXPENDABLE TUGS (OR TANK SETS)

**MISSION 58 CANNOT BE PERFORMED WITH THIS TUG

total program costs that should be compared, therefore, are those shown for the best single LO_2/LH_2 system (\$19,978 million undiscounted) the best OIS (\$21,947 million undiscounted), and the values associated with each mix. The results of this analysis show that even with only a 22.5 percent increase in RDT&E (over the costs of a single large cryogenic stage) for the all-reusable family, there is minimal economic benefit associated with this mix. The relative interaction of the family elements is based upon using the Tug design that minimizes individual program costs on a program-by-program basis. The stage-and-one-half family shows an increase in total program costs on a program-by-program basis. The stage-and-one-half family shows an increase in total program costs of 2.5 percent with respect to the best single stage LO_2/LH_2 data point at 50,200 lb W_p but is actually less costly on the basis of transportation costs alone. The introduction of a small reusable cryogenic system with an efficient OIS reduces total program costs with respect to the expendable vehicle alone by over \$800 million even with separate, additive development costs; however this family is 6 percent more costly than the 50,200 lb W_p reusable LO_2/LH_2 system alone. If the families are compared on a discounted cost basis rather than on undiscounted costs, there is one switch in the rankings caused when the all-reusable family becomes more costly (by two percent) than the single large reusable Tug; however, the difference is too small to be considered decisive.

Space Based Tug Systems

The final element in the Tug concept comparison was an evaluation of space basing. Since the space basing of reusable Tugs is a complex operational problem, the emphasis in this analysis was on bounding parametrically the magnitude of potential costs and cost savings attainable with this basing mode. No definitive estimate of these costs can be derived until the operational efficiency of the space-based Tug and its logistics system are well defined.

Important procedures and assumptions used for the space basing analysis, only, were as follows:

- The analysis was split into two elements, namely (1) Tug operations and (2) logistic system operations
- It was assumed that the logistics problem (e.g. resupply of Tug propellants and payloads) could be treated on an annual basis rather than mission-by-mission
- Tug operations were grouped by launch azimuth because of the large plane-change penalties associated with a single Tug operating azimuth
- The space based Tug concept was selected as a 50,200 lb LO_2/LH_2 configuration. Sizing optimization was not addressed in the analysis
- Space-based Tugs were assumed to receive, at resupply, only the propellants needed for the next mission; however, Tugs delivered to orbit for initial placement or recycling were considered to be fully loaded.
- Resupply propellants were assumed to be delivered by a Space Shuttle containing cryogenic tankage (inert weight 2000 lb) in its cargo bay. The amount of propellant carried was constrained by the Shuttle payload capacity, less this tankage weight. Transfer and chilldown losses were assumed to be one percent for LO_2 and two percent for LH_2 . Propellants were delivered directly to empty Tugs rather than to an orbiting propellant depot.
- Payloads were assumed to be delivered in clusters by the Shuttle
- Tug lifetime was assumed to be 30 uses, total; however, each Tug was returned to earth after 10 flights or two months on orbit.

Using these assumptions, three space basing cases were analyzed. The first two were based upon space-based Tug designs featuring modest (180 lb) increases in structural weight—primarily micrometeoroid shielding—and no change in avionics weights. Case 3 explored parametrically the consequences of a space-based Tug requiring augmented avionics for redundancy and autonomy; the avionics weights were increased 50 percent to bound this problem, and this resulted in an overall stage weight increase of approximately 600 lb (above ground based). The only differences between Cases 1 and 2 were the payload savings. Case 1 featured mode selections that would maximize the payload savings, whereas Case 2 captured the same payload effects as its equivalent ground based configuration. In this way, Case 2 isolated the transportation advantages of space basing and Case 1 quantified the advantages of trading payload savings against increased transportation costs.

The results of the space-basing analysis are summarized in Figure 8. As this graph indicates, space-based Cases 1 and 2 (virtually identical in cost) give undiscounted savings on the order of one billion dollars over comparable ground-based systems. Moreover, even Case 3 in which space-based Tug avionics increased by 50 percent can save more than half a billion dollars, undiscounted, over the ground-based configuration. These savings arise primarily from the more efficient use of the Shuttle in its logistics role. As noted earlier the operations of space-based Tugs are far less well defined than those of ground-based systems and consequently there is far greater uncertainty in the RDT&E and operations costs for space basing. Nonetheless the potential savings of space-based Tugs will permit considerable growth in these cost elements before a crossover point with ground basing is reached.

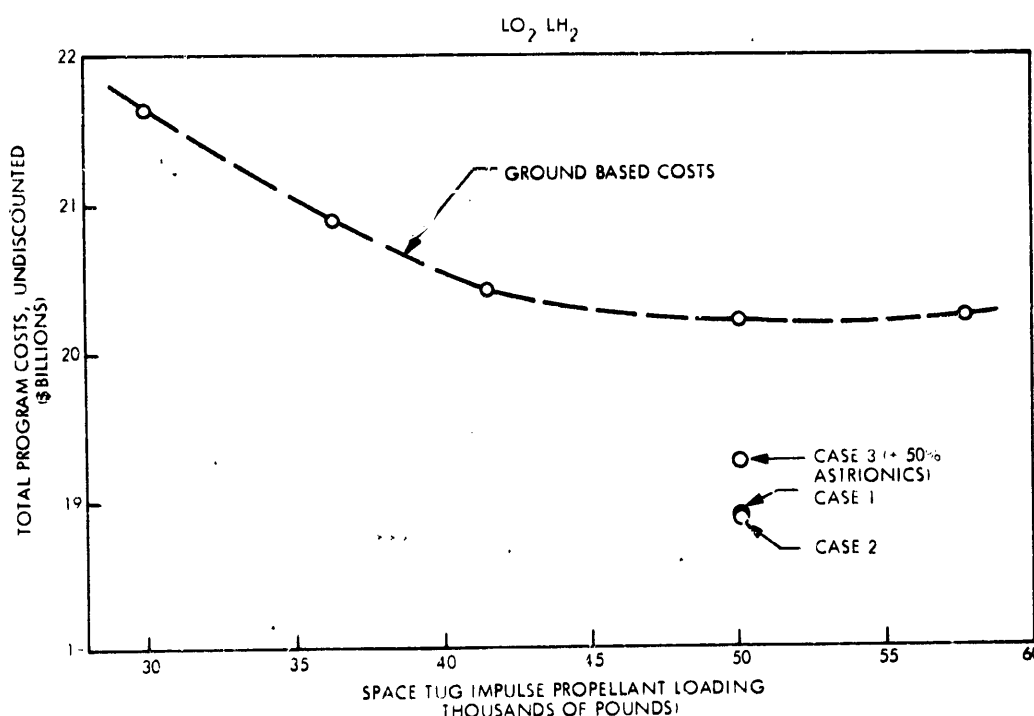


Figure 8. Ground Based/Space Based Tug Comparison

TUG SENSITIVITY ANALYSES

Another major aspect of the data interpretation task performed by Lockheed was the series of sensitivity analyses conducted to define the effect of major system variables on total program cost. These sensitivity analyses covered two general categories of variables:

- External Factors. These are factors outside the influence of the Tug program. They include Shuttle user fee, Shuttle payload capacity (weight and size), and payload weights and costs.
- Tug Variables. These are factors directly influenced by the design or operating mode of the Tug. They include Tug mass fraction, specific impulse, lifetime, and refurbishment factors.

The first set of sensitivities answers the general question: What happens to these study results if some of the major programmatic variables change? The second set answers a designer's or program planner's question: What does the economic analysis mean in terms of specific implications to Tug system definition?

All of the data supporting these sensitivity studies were generated with STAR/ANNEX computer runs. Mathematica ran additional sensitivity studies using the TUGRUN program, and also quantified data from the Lockheed sensitivity analyses on the basis of allowable RDT&E costs; this effort is discussed subsequently.

The sensitivity analyses performed by Lockheed are discussed in the following paragraphs.

Shuttle User Fee

A primary concern in evaluating the results of this study is the effect of increased Space Shuttle user fee. The study baseline value of \$5 million per flight was based on a two-stage, fully-reusable Shuttle. In the time that this study has been in process the Shuttle has been redefined as a reusable orbiter with expendable tankage and a solid propellant first stage; the user fee is now estimated at \$10.5 million per flight. To measure the impact of growth in the Shuttle user fee, STAR/ANNEX runs were made for two Tug concepts as the user fee was increased in two stages to \$15 million per flight. The selected concepts were the Large Tank Agena OIS and the 50,200 lb LO_2/LH_2 reusable Space Tug. Results of this analysis are shown in Figure 9, which plots (in undiscounted dollars) the growth in transportation cost, payload cost, and total-program cost as Shuttle user fee increases from \$5 million to \$15 million.

The Large Tank Agena transportation and total program costs increase proportionately as the Space Shuttle user fee increases, because payload costs remain constant. In the case of the reusable Tug, however, the total payload cost is affected slightly by the Shuttle user fee because of the mode selection process. As the user fee increases, it becomes uneconomical for some programs to use the retrieval modes; thus, payload savings are lost, resulting in higher payload costs. Note, however, that a crossover in total program cost between the orbit injection stage and the reusable Tug does not occur in the range of Shuttle user fee investigated here; moreover, this conclusion seems valid to some point in user fee beyond \$20 million per Shuttle flight.

Shuttle Payload-Carrying Capability

A second sensitivity dealing with the Space Shuttle is summarized in Figure 10. Because of some potential variations in Space Shuttle capacity, an analysis was undertaken in which the nominal Shuttle definition for this study was varied in two steps: (1) a reduction of 15 feet in cargo bay length (from 15 by 60 feet down to 15 by 45 feet), and (2) the above length reduction plus a reduction in the due-east 100 nm circular orbit payload-carrying capability of the Shuttle by 20,000 lb (from 65,000 lb down to 45,000 lb). This analysis was carried out for both the \$5 million and \$10 million Shuttle user fee values. Because of the anticipated effects of shortening the Shuttle cargo bay and reducing its load-carrying capability, a LO_2/LH_2 design smaller than the least-cost 50,200 lb system was chosen for this analysis. The Tug was assumed to have 36,200 lb of propellant.

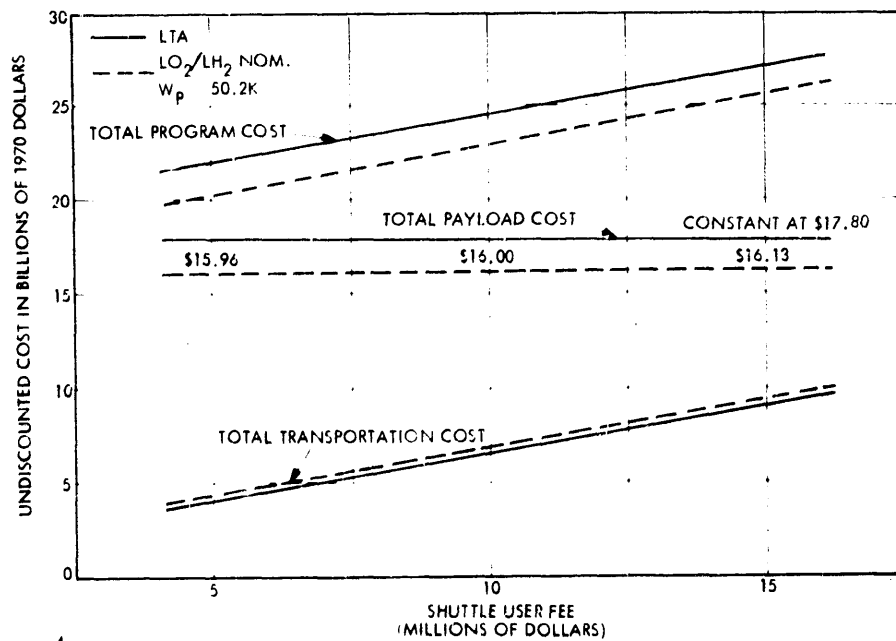


Figure 9. Cost Sensitivity to Shuttle User Fee

ADVANCED DESIGN LO_2 LH_2 SPACE TUG $W_p = 36.2K$ LB

\$5M SPACE SHUTTLE USER FEE

\$10M SPACE SHUTTLE USER FEE

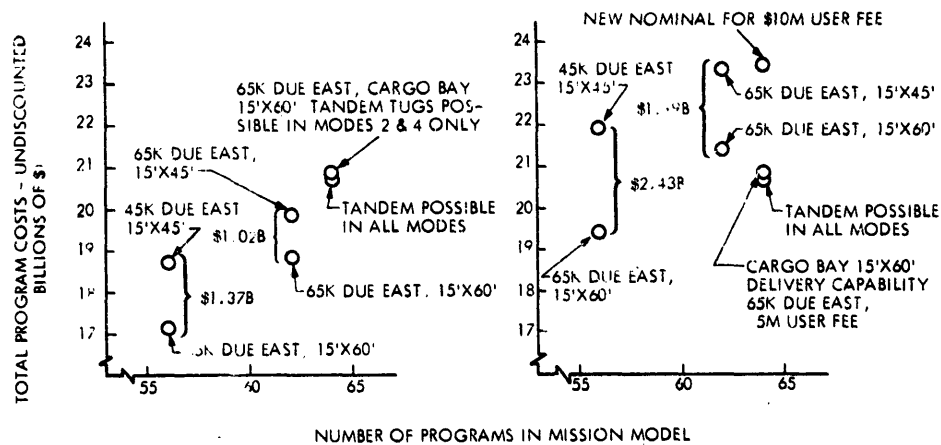


Figure 10. Cost Impact of Variations in Space Shuttle Capability

The first step in the Shuttle capacity perturbations (payload bay length reduction) had the effect of knocking out of the mission model two programs that had 60-foot-long spacecraft. The second step (45,000 lb due-east payload capability at 100 nm) knocked out an additional 6 missions, all in the highly inclined orbit categories, because the Shuttle was unable to take either the payload or the Tug and its required propellants to orbit. The bottom data points on both graphs, labelled 65,000 lb due-east, 15 by 60 ft, represent the nominal points with the full 64 programs reduced in cost by the deletion of the missions just mentioned. Evaluating these cases in terms of the Shuttle perturbations on the remaining missions produces the \$1.02 to \$1.37 billion increase in total program cost at a \$5 million user fee, and a corresponding \$1.99 to \$2.43 billion increase for a \$10 million Shuttle fee. These delta costs specifically exclude the economic impact of the inability to perform the 2 or 8 missions which fall out of the model, and thus reflect only the decrease in payload effects captured and the increased average transportation costs.

Unmanned Payload Influences

The final set of sensitivities run for variables external to the Tug program concerned the influences of unmanned payload weights and costs on the Tug system economics. The first of these sensitivities dealt with the effects of payload weight growth, while the second analyzed the relative contribution of the various sources of payload cost savings.

The effect of payload weight growth on total program cost was evaluated for three reusable Tug configurations. In the measurement of this sensitivity, all baseline payload weights for each program were increased by 15, 30, and 50 percent, resulting in three off-nominal mission models. For each perturbed mission model and each candidate Space Tug, the undiscounted total program cost was evaluated. The resulting increases in total program cost as a function of the percentage payload growth are presented in Figure 11 as discrete points for each Tug configuration. These results indicate that the LF_2/LH_2 Tug is least sensitive to across-the-board increases in payload. The reference $FLOX/CH_4$ Tug (divided tank design) is most sensitive.

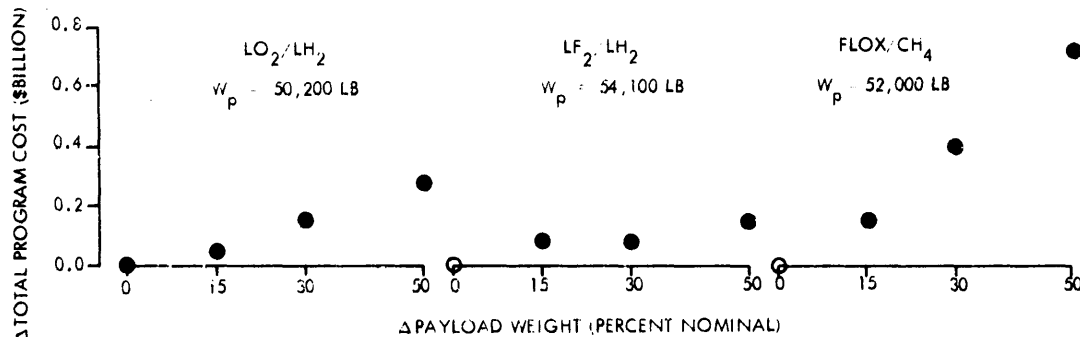


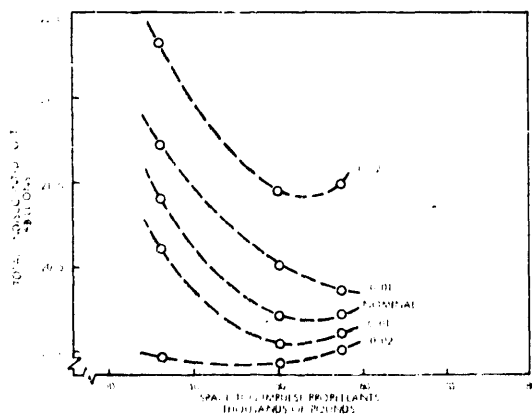
Figure 11. Cost Sensitivity to Payload Weight Growth

A brief analysis was undertaken to evaluate the relative magnitude of the three components of payload cost savings for a reusable Space Tug system, namely: weight-and-volume relaxation; payload reusability; and payload accessibility in case of failure. The contribution of each of these items to the payload savings for a typical reusable Tug (50,200 lb LO₂/LH₂ stage) was determined by calculating with STAR/ANNEX the total program costs for each level of payload effects. Results of this analysis show that of the total payload cost savings of \$3.962 billion undiscounted (difference between baseline-expendable and low-cost-reusable payloads with accessibility) \$1.384 billion is from reusability, \$1.55 billion from mass and volume effects, and \$1.028 billion from accessibility.

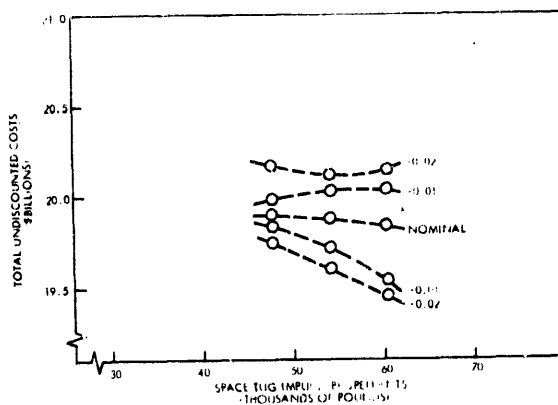
Tug Mass Fraction

The first of the sensitivity analyses conducted for Tug program variables was stage mass fraction (λ'). The variation in total program cost for changes of ± 0.01 and ± 0.02 from the baseline Tug mass fraction values was assessed for three propellant combinations, namely LO₂/LH₂, LF₂/LH₂ and FLOX/CH₄. The results of this analysis are summarized in Figure 12.

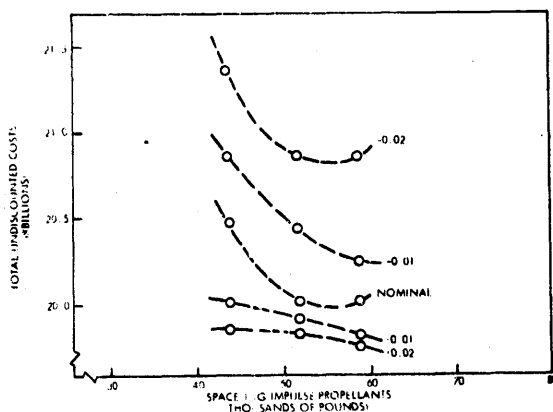
For the LO₂/LH₂ Tug, λ' variations were evaluated for Tugs of 36,300 lb, 50,200 lb, and 56,600 lb propellant weight; corresponding baseline mass fractions were 0.852,



(LO_2/LH_2 PROPELLANTS)



(LF_2/LH_2 PROPELLANTS)



(FLOX/CH_4 PROPELLANTS)

Figure 12. Total Program Cost Sensitivities to Tug Mass Fraction

0.873 and 0.880, respectively. This analysis shows that the sensitivities were not uniform for the various propellant loadings. The 36,300 lb Tug exhibited roughly comparable sensitivity for increases or decreases of λ' but the heavier Tugs showed a greater sensitivity to decreases in λ' than to increases. This suggests that the larger stages are operating efficiently for the baseline λ' values, and that improving the structural efficiency beyond these values yields diminishing returns.

For the LF_2/LH_2 Tug, λ' variations were evaluated for Tugs with propellant loadings of 47,800 lb, 54,100 lb, and 60,600 lb; the corresponding baseline mass fractions were 0.882, 0.889 and 0.895, respectively. Because of the higher structural efficiency of these Tugs (compared to LO_2/LH_2 configurations) and the higher I_{sp} of the LF_2/LH_2 propellant combination, the fluorine-hydrogen Tugs are generally less sensitive in total program cost to λ' than the LO_2/LH_2 Tugs. Note, however, that the larger LF_2/LH_2 Tugs are more sensitive to moderate (± 0.01) shifts in λ' than is the 47,800 lb configuration. This is the opposite of the trend observed in LO_2/LH_2 Tugs.

For the FLOX/CH_4 Tug, λ' variations were evaluated for Tugs with propellant loadings of 44,000 lb, 52,000 lb, and 58,900 lb; the corresponding baseline mass fractions were 0.888, 0.897, and 0.904, respectively. Though the FLOX/CH_4 Tug has a higher structural efficiency than LO_2/LH_2 Tugs, its lower specific impulse (414 sec vs 460 sec) causes these Tugs to be as sensitive to λ' variations as the LO_2/LH_2 stage. These sensitivities have characteristics similar to those of the LO_2/LH_2 Tugs. For the lower propellant weights, near-symmetrical cost savings and penalties result. However, for the larger propellant weights diminishing cost savings result for improvements in λ' , whereas severe cost penalties result for decreases in λ' .

All mass fraction sensitivities are proportionately greater than the specific impulse sensitivities (discussed subsequently).

Tug Engine Specific Impulse

The next Tug cost sensitivity investigated was specific impulse of the main engine. This analysis, conducted for the baseline LO_2/LH_2 propellant combination only,

explored a range of I_{sp} values from 470 sec for the upper bound to 444 sec for the lower capacity (compared to the 460 sec nominal value). For purposes of analysis only, the RL10 engine was used to represent the 444 sec case. Important assumptions made for this engine were as follows:

- The RL10 engine would be developed sufficiently to permit idle mode start, so that the stage pressurization system weights would not increase over the baseline Tug values
- The RL10 would be extended in lifetime to whatever level is needed for reusable Tug service.

A reduced development cost, covering the estimated value of these RL10 upratings, was used in place of the 460 sec engine development cost. An increased RDT&E cost was used for the 470 sec engine development.

The I_{sp} sensitivity study results (Figure 13) showed surprisingly small differences in total program cost over the range of propellant weights for 36,300 lb to 57,700 lb. The magnitude of the differences, in undiscounted dollars, ranged from about ± 70 million dollars at 50,200 lb to $\pm \$190$ millions at 36,300 lb.

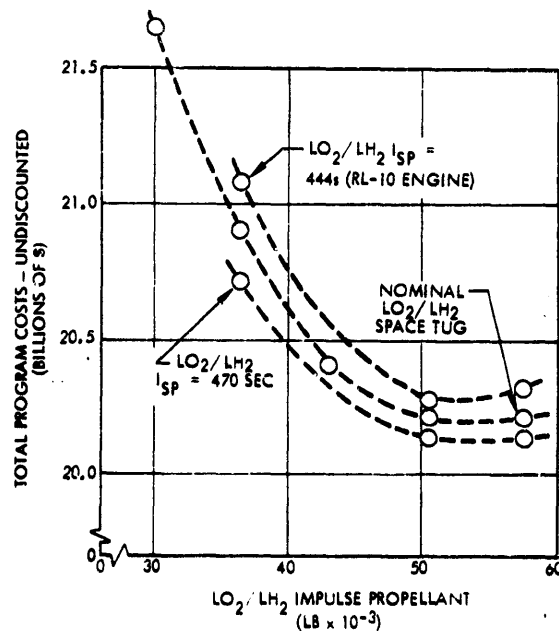


Figure 13. LO₂/LH₂ Space Tug I_{sp} Sensitivity

Tug Lifetime and Refurbishment Cost

The final sensitivity study conducted by Lockheed considered the impact of Tug lifetime and refurbishment costs on the total Tug program cost. This analysis was aimed at defining the benefits and costs parametrically, and not at establishing expected values for Tug life or refurbishment cost. The approach used in conducting this lifetime and refurbishment study was to calculate with STAR/ANNEX the total program costs for varying values of Tug lifetime, refurbishment cost, and first-unit cost. The results of this analysis are presented in Figure 14.

The upper graph plots undiscounted total program cost as a function of Tug lifetime for the 50,200 lb ground based LO_2/LH_2 configuration. This curve shows diminishing economic returns as lifetime is increased from 10 to 100 uses (holding refurbishment factor constant at the baseline value of 3 percent). The rapid decline in cost between 10 and 30 uses occurs primarily because a smaller fleet of reusable Tugs can be purchased as the lifetime of each Tug increases. Diminishing returns occur when the number of Tugs to be amortized reaches the minimum fleet size. In fact, Tug lifetimes of 100 uses require that expendable vehicles be purchased to perform the escape missions that would ordinarily be assigned to Tugs approaching their design lifetime.

The lower graph plots total program cost as a function of Tug refurbishment factor, holding lifetime constant at the baseline value of 30 uses. Refurbishment factor, ρ , is defined as the ratio of average refurbishment cost-per-flight to the cost of a new unit. The range of values explored for ρ was from one to ten percent, a range that encompasses the expected high and low variations in refurbishment factor based on historical analogies. For reference, the historically derived value of ρ for an analogous vehicle, the X-15, was estimated as 2.3 percent over 32 flights in calendar year 1965. This suggests that the value derived in the study cost methodology (3 percent) is reasonable. The results of this analysis show that, over the given range of ρ , the curve of total program cost is linear, indicating that the economic gain from reduced refurbishment costs is steady and free from diminishing returns.

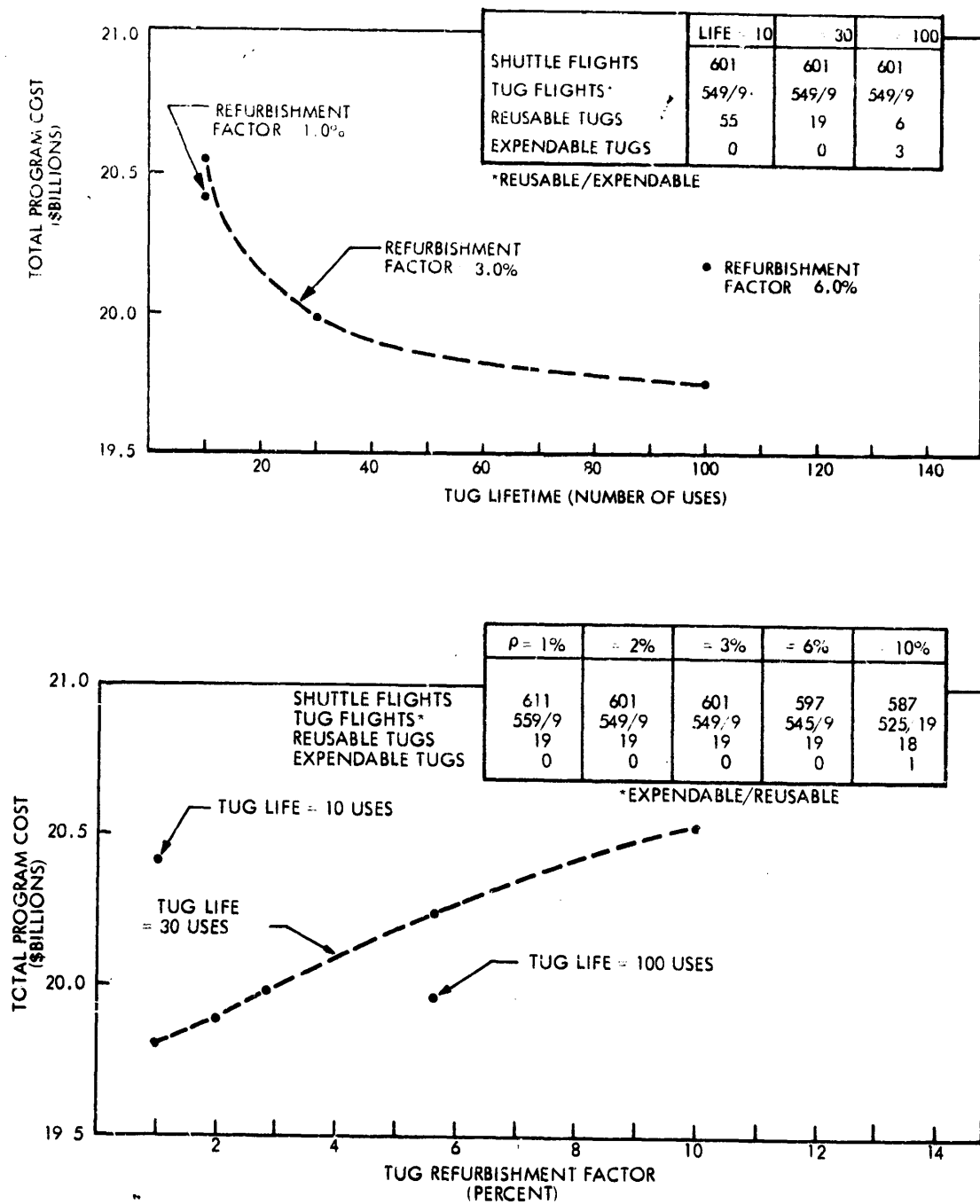


Figure 14. Cost Sensitivity to Tug Lifetime and Refurbishment Factor

Note that, in the range of Tug lifetimes and refurbishment factors analyzed here, the total program cost for the 50,200 lb $\text{I.O}_2/\text{LH}_2$ reusable Tug never rises to the level of the least costly orbit injection stage.

TUG FUNDING AND PHASING CONSIDERATIONS

To complete Lockheed's data integration and interpretation effort, an analysis was made of Tug funding requirements and OIS/Tug time-phasing implications.

The funding requirements for a typical orbit injection stage and a typical reusable Tug are compared in Figure 15. These expenditures include Tug/OIS funding for RDT&E, fleet investment, and twelve years operation; they specifically exclude payload costs and Shuttle user fees. The Tug RDT&E cost was spread over 5 years. The funding curves represent gross requirements by year; no smoothing was performed.

The purpose of this analysis was to establish the trends of early-year peak funding, operational-program support levels, and total Tug expenditures. The graph at the left presents expenditure requirements by fiscal year for the Large Tank Agena. Its funding curve reflects a typically low RDT&E expenditure, especially in the FY 1976-77 period when the Shuttle will be in final development, but peaks in the FY 1979-90 operational period. By contrast, the reusable Space Tug (right hand graph) has high funding requirements in the early time period (\$193 million RDT&E in FY 1976) but these requirements drop during the operational phase because of system operating efficiencies. Overall, the reusable Tug requires less total investment than the orbit injection stages.

No acceptable early-year funding limits for the Tug program were specified by NASA; however, the following general observations are valid with respect to Tug funding in the time period through FY 1978:

- To keep early Tug funding under \$50 million in the peak year, the Tug concept used in the initial operational capability (IOC) period of the Space Transportation System must be an orbit injection stage; this defers the introduction of a full capability reusable Tug until the CY 1981-1982 time period.

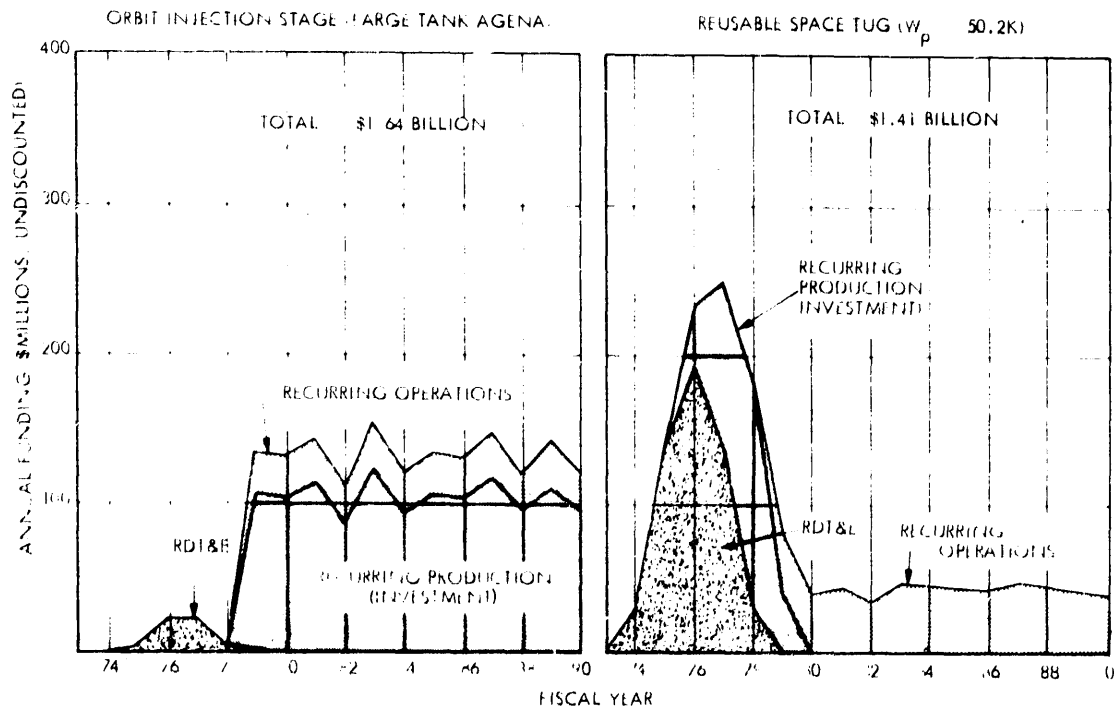


Figure 15. Tug Funding Comparison

- A compromise in the capability of the reusable Tug used at IOC of the Space Transportation System could potentially reduce Tug early year funding to around \$100 million in the peak year. This reduced capability might take the form of an earth-storable reusable Tug with payload retrieval capability, or a cryogenic reusable Tug without retrieval capability.

A cost impact analysis was undertaken by Lockheed to evaluate the penalty in total program cost for time-phased introduction of the reusable Space Tug. In this analysis it was assumed that an orbit injection stage would perform all the payload placements through 1984, and that the reusable Tug would completely supersede the OIS for missions performed after 1984. Payloads that were scheduled for launch before 1985 but that could be retrieved by the reusable Tug were sized and costed as reusable payloads launched by an OIS.

The results of this study indicate that the penalty for 1985 introduction of the reusable Tug is roughly \$770 million undiscounted, but only about \$88 million discounted. The

total-program funding requirements for 1979 and 1985 introduction of the 50,200 lb LO_2/LH_2 reusable Tug are compared in Figure 16.

ECONOMIC ANALYSIS

Using data from STAR/ANNEX computer punched-card and hard-copy formats, Mathematica extended and expanded the data interpretation process by means of an economic analysis. There were three main elements in this analysis:

- Evaluation of economic sensitivities
- Quantification of system variables
- Distribution of Tug benefits

These topics are discussed in the following sections.

Evaluation of Economic Sensitivities

To evaluate the effects of cost uncertainties and variables on Tug economics, Mathematica completed a series of sensitivity analyses that complemented, but did not duplicate, the Lockheed sensitivity studies (described earlier). Mathematica analyses covered the following topics: (1) the effects of major cost uncertainties, (2) the sensitivity of economic results to cost-driving variables, and (3) the influence of mission scenarios. The following paragraphs summarize findings in these three areas.

Cost Uncertainties. The impact of cost uncertainties in some of the more significant Tug system expenditures is explored in Figure 17. This figure is in the form of trade-off plots in which discounted (present value) costs are graphed in terms of nonrecurring expenditure requirements versus recurring cost savings foregone for each candidate Tug. Tradeoff lines on these charts represent the locus of Tugs with equal total program cost; consequently, the relative cost effectiveness of Tugs is measured from parallel projections of the tradeoff lines. The arrows measure the shift in relative cost effectiveness as the uncertainties are applied.

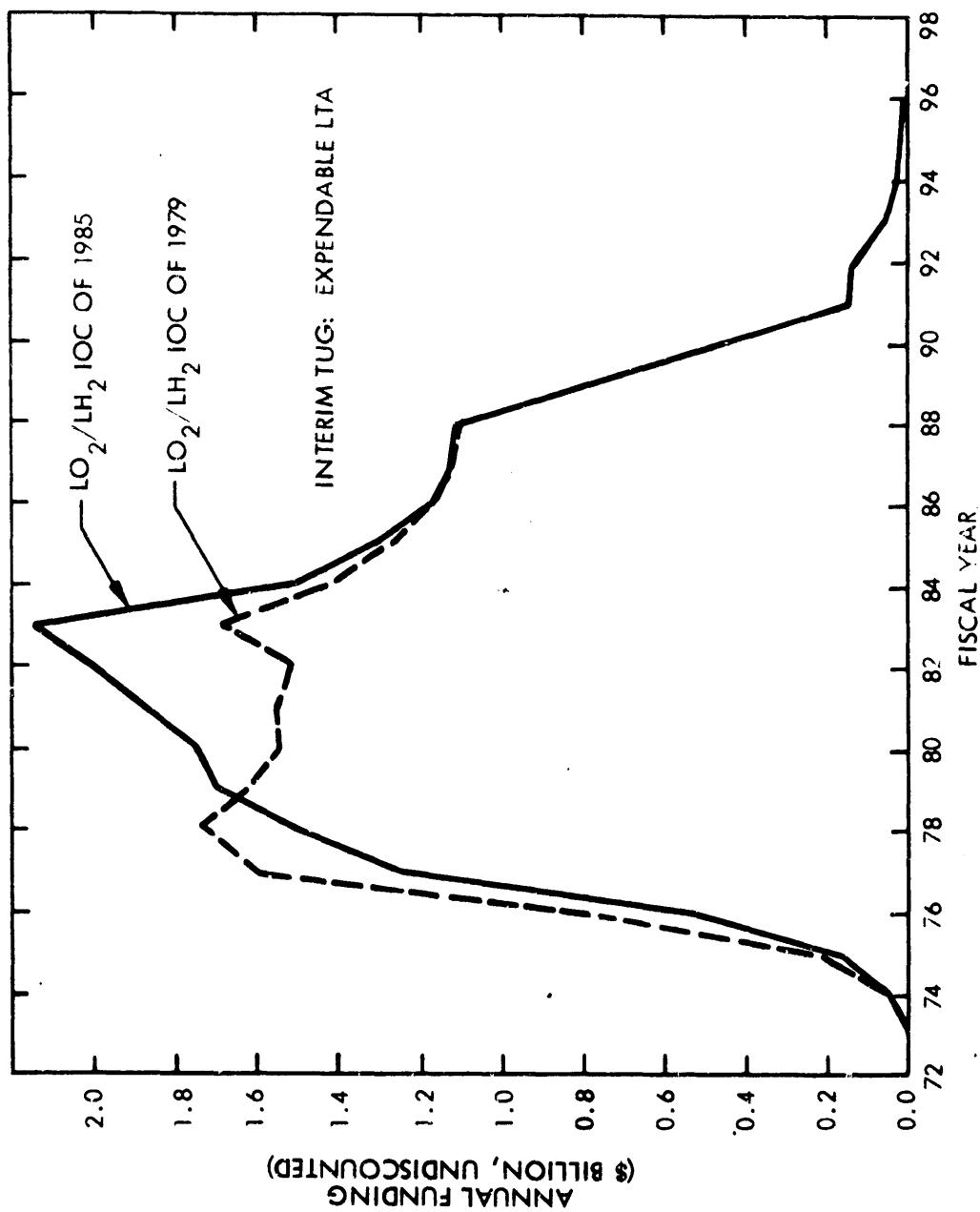
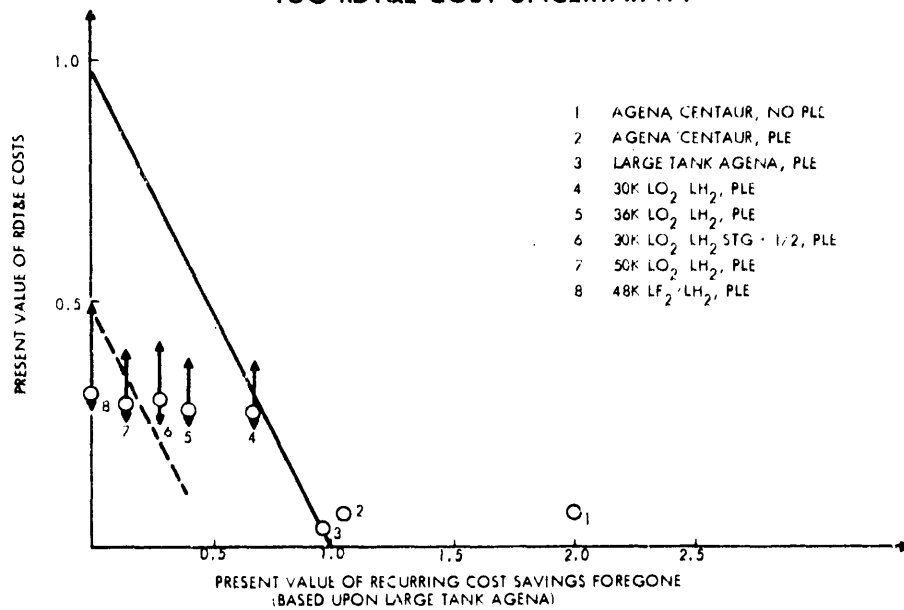


Figure 16. Comparison of Total Program Funding Requirements for a Delay of Six Years in Tug

TUG RDT&E COST UNCERTAINTY



PAYLOAD COST UNCERTAINTY

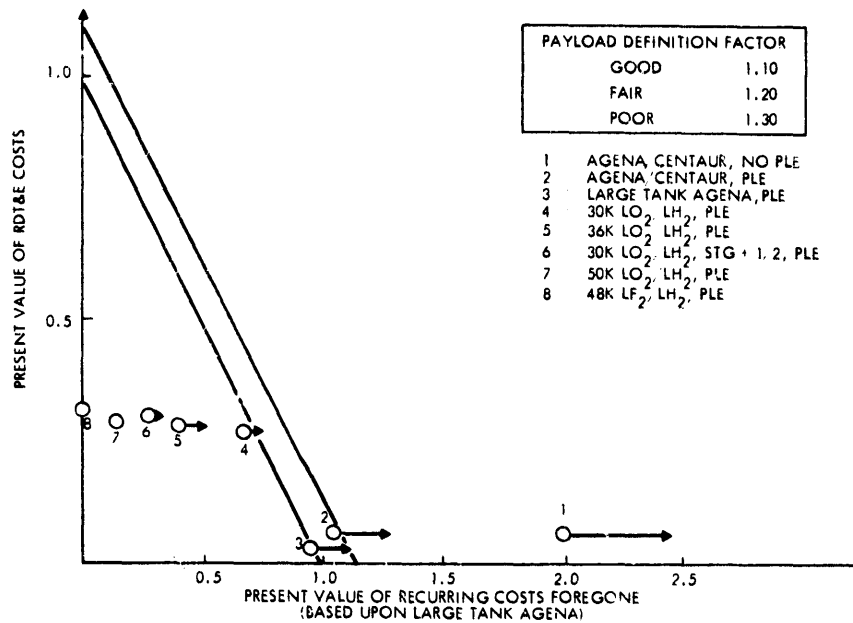


Figure 17. Effect of Cost Uncertainty on 'Tug' Economic Rankings

The upper graph shows the displacement in cost effectiveness rankings caused by uncertainty in Space Tug RDT&E cost. The basis for these variations was a set of estimated high and low bounds in the RDT&E cost of candidate Tug concepts. These values, which were derived on a preliminary judgment basis by Lockheed, were as follows:

Tug Concept	Uncertainty (percent)	
	Low	High
Orbit Injection Stages	-5	+10
LO ₂ /LH ₂ Reusable	-5	+40
LF ₂ /LH ₂ and FLOX/CH ₄ Reusable	-0	+60

The results of this analysis show that some reversals in the rankings of Tugs occur when the uncertainties are applied, while for other Tugs there is a tendency for concepts to move closer in cost effectiveness. For example the relative differences in RDT&E uncertainties drive the 30,000 lb reusable LO₂/LH₂ Tug above the Large Tank Agena OIS tradeoff line and cause the 36,300 lb LO₂/LH₂ Tug to move toward this line. Similarly, the 47,800 lb LF₂/LH₂ Tug has its margin of cost effectiveness over the 50,200 lb LO₂/LH₂ Tug cut by approximately half, though not eliminated, when the greater uncertainties of fluorine systems are incorporated.

The lower graph measures the effect of uncertainty in payload costs. This is an important sensitivity because payloads comprise, typically, 80 percent of the total program costs. In this analysis the payloads in the mission model were identified by NASA to be well, fair, or poorly defined. Accordingly, Mathematica assumed uncertainty factors of 1.10, 1.20, 1.30 for the three classes respectively. For simplicity, only the upper uncertainty bounds were considered. The results of this analysis show that as payload costs, especially unit investment, are driven upward by the uncertainty factors, the benefits from payload reuse are increased and the losses from expendable mode operation are increased. This is demonstrated in the chart, with the baseline Large Tank Agena orbit injection stage family foregoing an additional \$150 million in potential savings. The small 30,000 lb LO₂/LH₂ Tug loses only about \$50 million, and the 47,800 lb LF₂/LH₂ and 50,200 LO₂/LH₂ Tugs remain relatively unchanged. The

36,300 lb LO_2/LH_2 Tug actually fares somewhat worse than its smaller 30,000 lb counterpart because in the cost optimization process, payload reuse benefits were traded off against mass and volume effects.

Sensitivities to Major Variables. Mathematica explored parametrically the influence of major programmatic factors that could potentially alter the study results. Variables explored included Space Shuttle user fee and payload refurbishment factor. Typical results are presented in Figure 18.

The upper graph shows the variation in cost savings (relative to an orbit injection stage without payload effects) for various Tug concepts as Shuttle user fee is increased from \$5 million (reference study value) to \$10 million per flight. This analysis was performed without the least-mission-cost logic of the Lockheed STAR/ANNEX program; hence the results constitute a worst-case analysis. Lockheed results presented earlier show the behavior of costs in an optimized case. Results of the Mathematica Shuttle user fee sensitivity study show the following trends:

- Up to the current Shuttle user fee of \$10.5 million per flight, there is no crossover between expendable orbit injection stages and reusable Tugs
- Variations in the Space Shuttle user fee have the strongest impact on the larger Tugs within each class, and also on the stage-and-one-half concepts. This is because the higher propellant loadings for fully reusable Tugs (and the drop tank set for stage-and-one-half Tugs) serve to lengthen the overall stage length and thereby require more Shuttle flights. Obviously the Tugs requiring the most Shuttle flights are affected most by Shuttle user-fee rises.

The lower graph plots the variation in cost savings for changes ranging between half and double the baseline values for the payload refurbishment factor (ρ) used in the payload effects calculations. These baseline values of ρ ranged between 20 and 40 percent, with the majority in the 30 to 40 percent region.

As would be expected, all reusable Tug candidates display extreme sensitivity to payload refurbishment costs just over twice the nominal values. The 30,000 lb LO_2/LH_2 Tug is especially sensitive for reasons discussed previously. The fluorine Tugs, also highly sensitive, remain somewhat above the LO_2/LH_2 Tugs because of slightly higher capture of potential mass and volume effects and lower transportation costs.

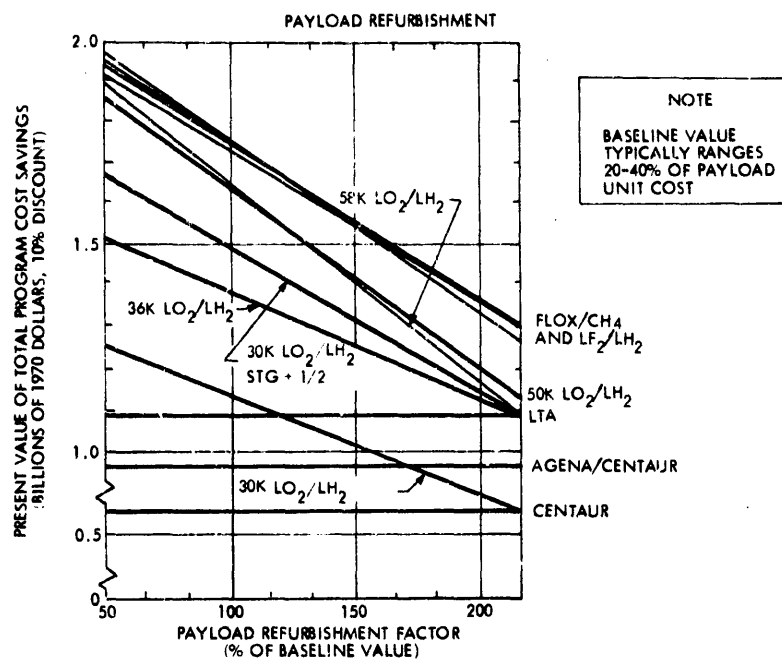
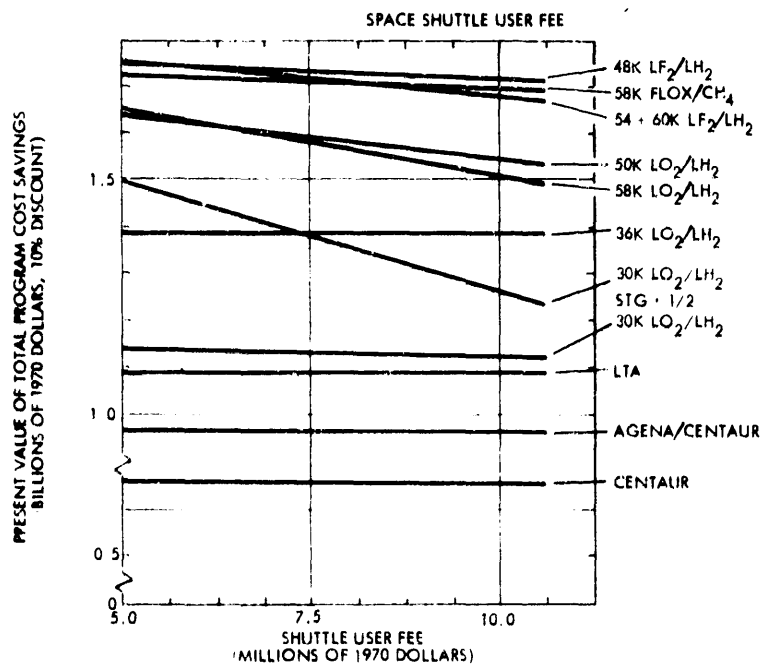


Figure 18. Economic Sensitivities to Major Variables

If payload refurbishment factors decline below the baseline values, as most recent payload effects analysis results indicate, further economic justification for a reusable Tug can be supported.

Effects of Mission Scenario. At the outset of the study a major concern was the dependence of the choice of cost-effective Tugs on the specific mission model used for the analysis. The mission model is a projection of possible future activity, based, of course, on current activity and experience; thus it cannot be depicted with a high degree of confidence for the programs of the 1980s. For this reason Mathematica undertook a systematic examination of the effects of mission scenario on Tug system economics. A major goal of the analysis was to determine whether the most important source of variation in Tug economic benefits lies with the scale or with the composition of mission activity.

A series of seven mission scenarios (one baseline and six alternatives) was analyzed by Mathematica. The mission scenarios incorporated variations in the composition and activity level of missions in the model, including variations in user agencies, velocity requirements, and payload lifetimes. Specific mission scenarios analyzed were as follows:

Scenario	Description	Number of Shuttles and Tugs as Percent of Baseline Traffic	
		Tugs	Shuttles
1	Baseline NASA-DOD Model	100	100
2	All 2 to 4 year satellites removed; 5 year and longer lifetime satellites tripled	101	99
3	OSS/OA Model reduced to 50%	79	80
4	DOD Model doubled	132	134
5	OSS/OA Model reduced to 50% and non-NASA doubled	105	105
6	Synchronous equatorial missions doubled	120	120
7	All 2 to 4 year satellites reduced to 75%; 5 year and longer satellites increased by 50%	100	100

Using the TUGRUN computer program, the total cost savings for these varying scenarios were calculated as a function of activity level on a Tug-by-Tug basis. Trend lines were drawn to establish patterns in the data points. Significant deviations from the pattern were analyzed and explained. Typical plots of this scenario analyses are presented in Figure 19.

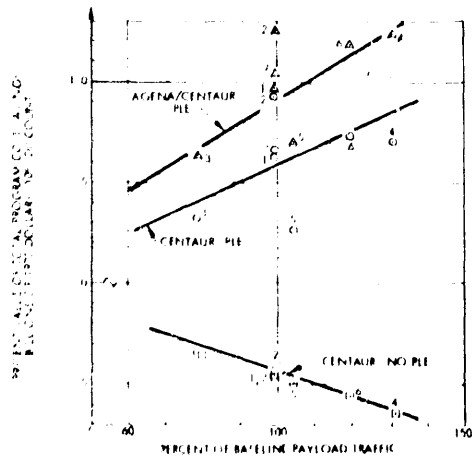
The trend lines from the various scenario analyses are plotted on a common scale in Figure 20. Important findings of this analysis were as follows:

- It is the activity level and not the composition of the mission scenario that is primarily responsible for the level of Tug economic benefits.
- The better performing Tugs predictably accrue benefits at a faster rate, as activity increases, than their counterparts with lower capacity.

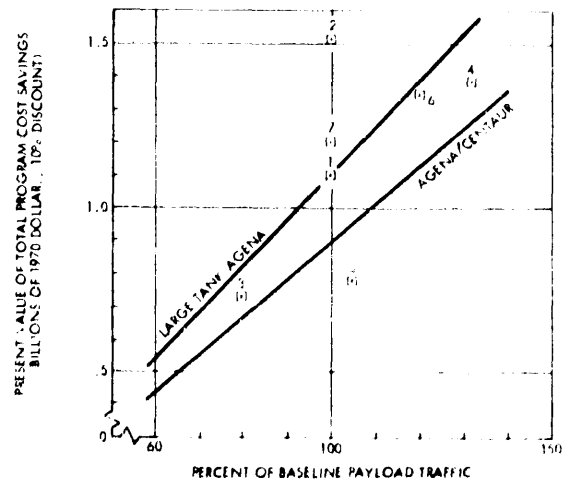
Quantification of System Variables

The second major element of the Mathematica economic analysis was the quantification of Tug concept comparisons and important Tug system sensitivities. This analysis served to put the potential savings for alternative Tug configurations into terms that a designer or planner can use, namely allowable RDT&E cost for a given Tug concept or alternative (in comparison to some other Tug concept). The Mathematica approach evaluated Tug benefits from the standpoint of savings incurred not only in the 1979-1990 time period of the mission model, but for the indefinite future (the so-called infinite horizon effect). The allowable RDT&E cost comprises the time-phased expenditures that can be incurred, given the recurring cost savings over the baseline case, while still allowing the selected Tug concept to be cost effective at a 10 percent social discount rate.

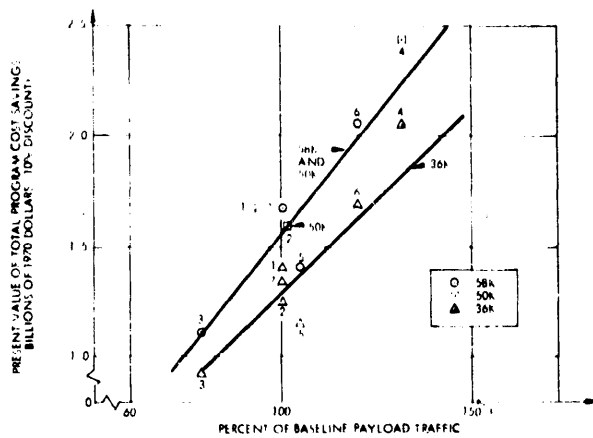
EXISTING ORBIT INJECTION STAGES



LARGE TANK AGENA



LO₂/LH₂ TUGS



LF₂/LH₂ AND FLOX/CH₄ TUGS

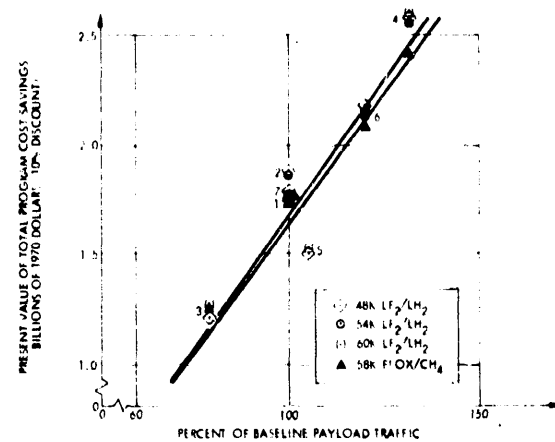


Figure 19. Typical Scenario Analysis Data Plots

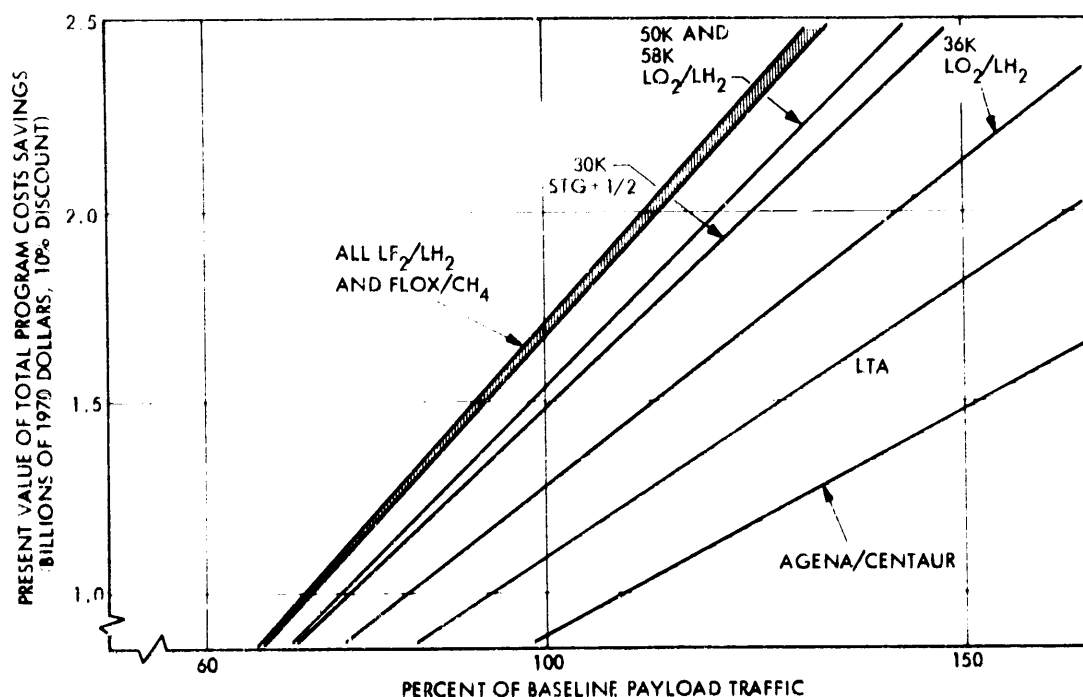


Figure 20. Summary of Scenario Analysis Results

The principal Tug concepts are compared from the standpoint of allowable RDT&E cost as follows (all costs in millions of undiscounted 1970 dollars):

Tug Configuration	Computed Allowable RDT&E Cost	Estimated RDT&E Cost	Economic Margin
30K LO ₂ /LH ₂	574	502	72
36K LO ₂ /LH ₂	1062	510	552
50K LO ₂ /LH ₂	1554	528	1026
48K LF ₂ /LH ₂	1809	576	1233
Family: 30K LO ₂ /LH ₂ + Drop Tanks	1296	551	745
Family: 20K & 50K LO ₂ /LH ₂	1819	647	1172
Family: 20K LO ₂ /LH ₂ + Drop Tanks	1335	533	802
Family: 20K LO ₂ /LH ₂ + LTA	828	539	289
Space Based (Case 3)	2227	569	1658

These allowable RDT&E costs are referenced against the most cost effective orbit injection stage (the Large Tank Agena). It is not expected that the entire allowable RDT&E cost would be expended to develop a Tug, so to express the net benefit of any given Tug, the concept of economic margin was introduced. This margin is simply the allowable RDT&E cost less the estimated actual RDT&E cost. The economic margin provides insight in two aspects: (1) it indicates the margin to cover error in the estimation of cost and benefits, and (2) it indicates the return of a Tug concept (over its cost measured in undiscounted dollars) to the Shuttle/Tug Space Transportation System.

In evaluating the Tug concept comparison presented above, note that the greatest potential economic margin lies with the space-based Tug (Case 3, the most conservative space-based case, was selected to obtain a measure of the minimum margin over ground basing). Among the ground-based Tug concepts, the 47,800 lb reusable LF_2/LH_2 Tug configuration ranked highest, followed by the 20,000/50,200 lb reusable LO_2/LH_2 Tug family, and the 50,200 lb LO_2/LH_2 reusable Tug alone. However, the space-based Tug, the LF_2/LH_2 Tug, and the LO_2/LH_2 family all have greater cost uncertainty than the 50,200 lb LO_2/LH_2 Tug. Note that all configurations listed here have some margin over the Large Tank Agena, although the 30,000 lb reusable LO_2/LH_2 has a margin of less than 10 percent.

In quantifying the allowable RDT&E costs associated with key Tug sensitivity factors, the important parameters are the absolute and relative values of allowable RDT&E cost between levels of capability. For example, in evaluating specific impulse for reusable LO_2/LH_2 Tugs the allowable RDT&E cost variation is as follows:

Propellant Weight	I_{sp} (sec)	Allowable RDT&E Cost (\$ millions)	
		Absolute Value	Δ from Nominal
36,300	444	857	-205
	460 (nominal)	1062	0
	470	1274	+212
50,200	444	1507	-47
	460 (nominal)	1554	0
	470	1636	+82
57,700	444	1537	-33
	460 (nominal)	1570	0
	470	1614	+44

The absolute values reveal that none of the I_{sp} variations considered degrade the performance of LO_2/LH_2 reusable Tugs to the point where they do not compete with orbit injection stages. The relative magnitudes signify that, for example, only \$47 million can be invested in excess of the level of RL10 expenditures to get a 460 sec I_{sp} engine for the 50,200 lb LO_2/LH_2 reusable Tug, and only \$82 million beyond the latter level to get 470 sec I_{sp} (\$129 million above RL10). Note that there is a far better payoff on RDT&E investment for I_{sp} improvements in the smaller Tugs. On the basis of the foregoing analysis it may also be concluded that the RL10 engine is a cost-effective engine selection for Tugs of 50,200 lb propellant loading and larger.

In evaluating mass fraction variations, the same comparison techniques apply. Typical values for reusable LO_2/LH_2 Tugs are as follows:

Propellant Weight	Mass Fraction	Allowable RDT&E Cost (\$ millions)	
		Absolute Value	Δ from Nominal
36,300	0.832	-98	-1160
	0.842	673	- 389
	0.852 (nominal)	1062	0
	0.862	1381	+ 319
	0.872	1879	+ 817
50,200	0.853	931	- 623
	0.863	1327	- 227
	0.873 (nominal)	1554	0
	0.883	1712	+ 158
	0.893	1788	+ 234

Note that the absolute values go negative for the 36,300 lb LO_2/LH_2 Tug at $\lambda' = 0.832$ indicating a crossover with the LTA in cost effectiveness. However the 50,200 lb Tug always maintains a sizeable margin over the LTA at all values of λ' investigated. The relative values of allowable RDT&E cost indicate that sizeable investments in improving the mass fraction of a smaller LO_2/LH_2 Tug will pay off, but that the payoff for a 50,200 lb size LO_2/LH_2 Tug can only be realized by preventing λ' from dropping below the 0.87 to 0.86 range. These allowable RDT&E costs can be used as target figures for permissible expenditures in advanced structures technology, lightweight avionics, and other weight-saving techniques.

Allowable RDT&E costs for variations in Tug lifetime and refurbishment factor (based on a 50,200 lb LO₂/LH₂ reusable Tug) are as follows:

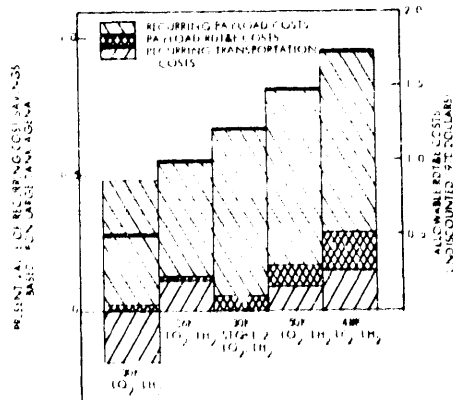
Lifetime (No. of Uses)	Refurbishment Factor (Percent)	Allowable RDT&E Cost (Millions)	
		Absolute Value	Δ from Nominal
30 (nominal)	10	1184	-370
30 (nominal)	6	1377	-177
30 (nominal)	3 (nominal)	1554	0
30 (nominal)	2	1607	+ 53
30 (nominal)	1	1670	+116
10	3 (nominal)	831	-723
30 (nominal)	3 (nominal)	1554	0
100	3 (nominal)	1808	+254

In the upper set of values, lifetime is held constant at the nominal value of 30 uses while refurbishment factor is varied; in the lower set of values, refurbishment factor is held constant at the nominal 3 percent while lifetime is varied. Evaluation of the absolute value of these allowable RDT&E costs shows that the reusable 50,200 LO₂/LH₂ Tug does not drop below the cost effectiveness of the LTA for any of the variables considered. The relative values in allowable RDT&E cost indicate that the most profitable area for investment is extending Tug life from 10 to 30 uses. All other improvements in lifetime or refurbishment factor yield steady but unspectacular gains.

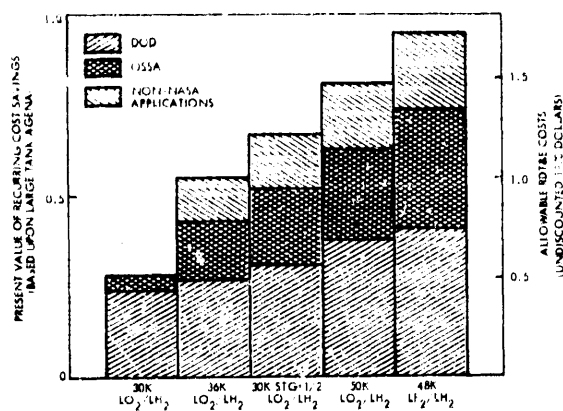
Distribution of Tug Benefits

The third major element of the Mathematica economic analysis was the distribution of benefits gained by candidate Tug concepts. Typical results of this analysis are shown in Figure 21.

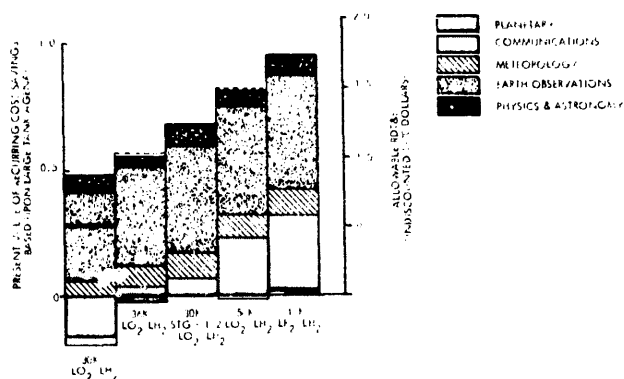
The distribution of Tug benefits by system element reveals that the primary source of these benefits is recurring payload cost savings (i.e., cost of replacement spacecraft that need not be purchased because of retrieval and reuse). Transportation cost savings contribute relatively little in Tug benefits and these savings alone cannot justify the development of a reusable Space Tug.



BY SYSTEM ELEMENT



BY AGENCY



BY PROGRAM AREA

Figure 21. Distribution of Tug Benefits

When the benefits are distributed by using agency or (agency grouping) it becomes evident that, for the most cost-effective Tugs, the savings arising from payload reuse and reduced transportation costs accruing to any one of these agencies are, alone, sufficient to justify the Space Tug development.

When the benefits are distributed by program area (independent of which agency performs them), the largest savings accrue to the general category of Earth Observations, and the next largest savings are for the Communications class of missions. The Planetary programs benefit least from reusable Tug development.

OBSERVATIONS

The findings of the Space Tug Economic Analysis study may be conveniently grouped under the following issues and topics:

- Reusable Tug vs Orbit Injection Stage
- Reusable Tug Selection
- Operational Mode Selection
- Overall Trends in the Data
- Implications to Tug System Definition

These issues are discussed in the following paragraphs. All of the results and conclusions, though subject to the assumptions and guidelines imposed on the study, were examined on a parametric basis that was broad enough to test their validity over a significant range of variables.

Reusable Tug vs Orbit Injection Stage

The first issue in the Tug selection process is whether to develop a reusable Space Tug or an orbit injection stage. In making this selection the result will depend on the criteria applied at the time of decision. Specific study findings applicable to each of five significant OIS/Tug selection criteria are as follows:

- Total Program Cost. Efficient reusable Tug concepts have a margin in benefits over the OIS of up to \$1.8 billion (ground based). This margin is large enough to pay the estimated Tug RDT&E cost and return an additional \$1.2 billion toward the initial cost of the new Space Transportation System.
- Transportation Cost. The cost savings caused solely by Tug reusability will pay for Tug RDT&E on an undiscounted-cost basis, but not on a discounted basis.
- Early Peak Funding. The OIS development funding requirements in the peak year of FY 1976 are roughly an order of magnitude lower than the reusable Tug.
- Development Cost Uncertainty. The greatest development risk and the maximum RDT&E cost uncertainty are associated with the reusable Tug; however, the cost uncertainties are not sufficient to offset the economic margin of efficient reusable Tugs.

- Payload Cost Factors. The reusable Tugs profit most from a decrease in payload refurbishment factor, and current payload-effects analysis indicates that lowered refurbishment factors are most likely. The orbit injection stages are also penalized most by high-bound uncertainties in payload cost.

In summary, the reusable Space Tug is a cost-effective investment even when the major programmatic and design variables are evaluated. The only circumstance that would favor selection of an orbit injection stage would be lack of funding to develop the reusable Tug. The penalty for deferring introduction of the reusable Tug until 1985 (using the Large Tank Agena OIS in the meantime) is \$770 million undiscounted, or \$88 million discounted.

Reusable Tug Selection

If sufficient funding is available to develop a reusable Tug, the next issue is to determine which reusable Tug configuration is most suitable. Study findings bearing on each of four reusable Tug selection criteria are as follows:

- Total Program Cost. Single stage configurations have greater economic margins than stage-and-one half concepts using the same propellants. The most cost effective propellant combinations are LF_2/LH_2 and $FLOX/CH_4$; however, LO_2/LH_2 reusable Tugs, if properly sized, are within about 15 percent of the economic margin of fluorine-based combinations. Families of reusable Tugs with common propellants and multiple sizes provide slight economic margins (in discounted cost, though not in undiscounted costs) over single size Tugs.
- Sensitivity to Programmatic Variables. Tugs with LF_2/LH_2 propellants are least sensitive to across-the-board increases in payload weights. The LF_2/LH_2 and $FLOX/CH_4$ propellants accrue economic benefits most rapidly as mission-model activity level is increased. The stage-and-one-half configurations are more sensitive to Shuttle user fee increases than single-stage configurations.
- Sensitivity to Design Variables. The LF_2/LH_2 Tugs are least sensitive to inert weight growth.
- Cost Uncertainty. The LF_2/LH_2 and $FLOX/CH_4$ Tugs incur greater development risk and cost uncertainty than LO_2/LH_2 concepts; these uncertainty factors drive LF_2/LH_2 and $FLOX/CH_4$ propellants toward LO_2/LH_2 on a cost effectiveness scale, although no crossover occurs.

In summary, then, the preferred reusable Tug design concept is single stage design. The best performing propellant combination from an economic standpoint is LF_2/LH_2 ;

this combination also provides the best hedge against Tug system variables. FLOX/CH₄ is competitive with LF₂/LH₂ but is more sensitive to the system variables. LO₂/LH₂ propellants offer acceptable performance at lower risk. Tug families show no clear-cut economic advantage.

Operational Mode Selection

The next element of Tug selection is the choice of operating modes. This is further divided into a selection of flight modes and basing modes. With respect to flight modes, the results of STAR/ANNEX least-program-cost calculations show that there is an economic advantage in using a mixture of all four reference Tug/payload modes (i.e., equal payload roundtrip, payload retrieval only, payload placement only, all-expendable). Other STAR/ANNEX comparisons involving varying levels of tandem flight capability show that costs are minimized if the possibility of using tandem Tugs in all four flight modes is allowed. Note that tandem mode operation is not normally selected in STAR/ANNEX, especially at higher Shuttle user fees, unless a specific cost advantage is derived through payload retrieval or other savings.

With respect to the Tug basing, the analysis of total program costs shows a great potential advantage for space basing. The primary basis for this advantage is the fact that the Shuttle is used more efficiently in resupply of a space-based Tug than in recycling a ground-based Tug to and from orbit. For example, the Space Shuttle can deliver bulk propellants for several Tug missions or multiple Tug payloads in a single Shuttle flight. However, space basing is subject to far greater uncertainties than ground basing, especially in the areas of logistic system operations and scheduling, Tug duration in orbit, and vehicle refurbishment requirements.

Overall Trends in the Data

Important overall trends in the study findings, some of which were quite unexpected, are as follows:

- The phenomenon of diminishing economic returns was observed in many of the Tug variables. This took the form of reduced allowable RDT&E costs as Tug performance improved beyond threshold values.

- The importance of synchronous equatorial missions in the economic framework was somewhat less than anticipated. The economic analysis showed that, although Tugs must be designed for reasonable payload capability to geostationary orbit, a Tug so designed can be economically justified without these missions.
- Tug costs (RDT&E, investment, 12 years operation) were found to be a third order effect behind payload costs and Shuttle user fees.
- The ranking of payload cost savings for a reusable Tug using baseline study assumptions was: (1) Mass and volume relaxation, (2) Payload reuse, and (3) Accessibility of failed spacecraft. The mass and volume savings and some accessibility savings can be captured by orbit injection stages; hence spacecraft retrieval is the source of all payload cost advantages of the reusable Tug. More recent trends in payload effects analysis will tend to make payload reuse the dominant source of savings for the reusable Tugs.

Implications to Tug System Definition

The economic comparisons and sensitivities analyzed in the study bear directly on how the Tug should be designed and deployed. Specific implications of a reusable Space Tug are as follows:

- Propellant Loading. In all propellant combinations considered for the reusable Tug, propellant loadings of around 50,000 lb gave least total program cost combined with favorable sensitivities to system variables (e.g., Shuttle user fee growth)
- Mass Fraction. The reference study values for Tugs sized at approximately 50,000 lb propellant lie near the threshold of diminishing economic returns, and hence are economically efficient design goals for the reusable Tug. These values are: LO_2/LH_2 , 0.87; LF_2/LH_2 , 0.88; and FLOX/CH_4 , 0.90.
- Engine Selection. For LO_2/LH_2 propellants the existing RL10 engine, modified for reusable Tug service, is a cost-effective selection.
- Tug Lifetime. A design lifetime of approximately 30 uses ensures that maximum economic gains from reusability will be attained. There are diminishing returns beyond a 30 to 40 use lifetime.
- Tug Refurbishment Factor. A design goal of two to three percent average refurbishment factor over the Tug lifetime is economically efficient and appears historically valid.
- Fleet Size and Composition. Reusable Tug fleet sizes of just under 20 vehicles are adequate to support the reference study mission model if tandem Tug operation is permitted in all modes. If tandem capability is restricted, then added expendable Tugs must be purchased to accomplish certain of the missions. For the given mission model and study guidelines (i.e., no phased introduction of the Shuttle/Tug system, no Tug funding limitations) there appears to be no economic justification for varying the Tug fleet composition to include mixes or families of configurations. This would likely change for constrained mission models or phased STS programs.

- Launch Vehicle (Space Shuttle). The capability of the Tug system in terms of number of missions captured and economic efficiency is seriously degraded if the Shuttle cargo bay size or payload weight capability is significantly reduced.

With respect to orbit injection stages, the economic analysis shows that the characteristics most needed in such vehicles are:

- Low unit production and operations costs
- High mass fraction and minimum stage length
- Performance closely matched to the requirements of the missions in the model (i.e., no overcapacity or undercapacity)
- Mission flexibility (adequate restart capability and lifetime on orbit)

STUDY ACHIEVEMENTS

In the Space Tug Economic Analysis, Lockheed and Mathematica have succeeded in developing the analytical techniques and the computer tools that can define a complete space transportation system and measure its overall economic behavior as system elements are substituted or varied in configuration. Specific accomplishments are as follows:

- The ability to define a space vehicle system on the basis of total program cost
- The ability to measure differences in vehicle design and flight mode on the basis of total program cost
- The ability to quantify differences of design concept, configuration and operations in terms that program planners can use, namely allowable RDT&E cost
- The ability to compare technology improvements (e.g., λ' and I_{sp}), and to assign quantifiable expenditures to variations in these parameters.

RECOMMENDATIONS

STUDY LIMITATIONS

Particular effort was made to generalize study results and make them free from limitations. However, some potential limitations on the data do arise from the following sources:

- In bounding the Tug-selection problem, the bounding assumptions excluded certain missions, configurations, and conditions. The following Tug system factors were excluded: (1) manned missions, (2) solid propellant stages, (3) interim vehicles, such as reusable Tugs with storable propellants, (4) funding-constrained Tug programs, (5) phased Shuttle implementation, and (6) rate-variable Shuttle user fees.
- To assess Tug benefits on a conservative basis, some of the added payload savings explored in the Payload Effects Analysis study follow-on were omitted. These include on-orbit repair/servicing, standardization, and reduced payload refurbishment factors.
- The available study resources did not permit consideration of complex operational problems such as multiple payload delivery by single Tugs.
- Some study assumptions made at the beginning of the contract, such as the \$5 million Shuttle user fee, were obsolete by the end of the study.

To offset the effect of these limitations, a wide range of programmatic variables was investigated. These sensitivities showed that, within the bounds of the analysis, none of the major study findings (economic margin of reusable Tugs; rankings of configurations, flight modes, and propellant combinations) were altered by significant changes of system variables. These sensitivities also provide trends for extrapolating study results outside the bounds of the analysis.

IMPLICATIONS FOR RESEARCH

Study results show that payload savings other than mass/volume relaxation effects are the primary economic justification for a reusable Space Tug. Consequently the most

important implication for such a Tug from the advanced technology standpoint is that long-leadtime development of hardware and techniques for performing the payload retrieval function is a high priority item for the Space Transportation System technology base. A program of analysis and test, using prototype hardware, should be funded under Supporting Research and Technology (SR&T) expenditures. By initiating this technology effort early there will be two important economic advantages:

- Tugs capable of capturing the potential net savings of more than \$1 billion will be operational in time to achieve the bulk of these savings
- The peak RDT&E funding for the Tug can be reduced somewhat

Another economic implication for research in the Tug area is the relative benefit of mass-fraction and specific-impulse improvements. The economic analysis shows that, proportionately, there is a much higher payoff for LO_2/LH_2 Tug mass fraction improvement than in engine I_{sp} uprating. Consequently the focus in Tug technology programs should be on techniques for significantly reducing stage inert weight.

Since the economic analysis shows a potential advantage for LF_2/LH_2 propellants over the other combinations considered, another promising area for SR&T effort is fluorine propulsion system technology, with emphasis on Shuttle compatibility issues.

SUGGESTED ADDITIONAL EFFORT

Additional effort in the economic analysis of Space Tug alternatives will benefit the entire Space Transportation System development program. The emphasis in this follow-on effort should shift away from the present study objectives of bounding the problem and establishing trends. Instead, the focus should be on refining data within the bounds of the present study; exploring the impact of topics beyond the bounds of the current study; and maintaining continuous support of the Tug design and operations definition effort.

Specific tasks suggested for the follow-on effort are as follows:

- Requantify the data within the study bounds to give planners an updated comparison of Tugs in the currently expected framework of the Space Transportation System, namely: \$10.5 million Shuttle user fee, activity- and funding-constrained STS program, the option of interim Tug systems, and current payload-savings factors.

- Explore topics outside the bounds of the present study, such as the economic impact of Tug growth for lunar missions, and the use of the Tug as an integral payload bus.
- Perform analyses too costly for the original study, such as the clustering of multiple payloads on a single Tug flight.
- Operate STAR/ANNEX as a direct support tool during Tug development to evaluate major design and operational alternatives.